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# Mobile CubeSat Command and Control assembly and lessons learned

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# NAVAL POSTGRADUATE SCHOOL

**MONTEREY, CALIFORNIA**

# THESIS

**MOBILE CUBESAT COMMAND AND CONTROL: ASSEMBLY AND LESSONS LEARNED**

by

Gregory C. Morrison

September 2011

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The Mobile CubeSat Command and Control (MC3) system provides ground support for the Colony II program. The combination of commercial off-the-shelf hardware with government off-the-shelf control software make for a low cost ground station solution. The Naval Postgraduate School will partner with select educational facilities to provide a world-wide footprint for Colony II satellite operations. To assist these partner facilities, the author created a detailed assembly and setup guide targeted to an average college student, a typical user for the MC3 ground station. This thesis captures the assembly process and documents lessons learned to help future operators of MC3 ground stations in their educational endeavors. Also included is an analysis and discussion of the Global Educational Network for Satellite Operations network and its suitability for performing the Colony II ground segment mission and possibly supplementing the MC3 network.

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**MOBILE CUBESAT COMMAND AND CONTROL: ASSEMBLY AND LESSONS LEARNED**

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Submitted in partial fulfillment of the
requirements for the degree of

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from the

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# ABSTRACT

The Mobile CubeSat Command and Control (MC3) system provides ground support for the Colony II program. The combination of commercial off-the-shelf hardware with government off-the-shelf control software make for a low cost ground station solution. The Naval Postgraduate School will partner with select educational facilities to provide a world-wide footprint for Colony II satellite operations. To assist these partner facilities, the author created a detailed assembly and setup guide targeted to an average college student, a typical user for the MC3 ground station. This thesis captures the assembly process and documents lessons learned to help future operators of MC3 ground stations in their educational endeavors. Also included is an analysis and discussion of the Global Educational Network for Satellite Operations network and its suitability for performing the Colony II ground segment mission and possibly supplementing the MC3 network.

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# LIST OF ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| ACL | Access Control List |
| AFIT | Air Force Institute of Technology |
| AUS | Authentication Server |
| AZ | Azimuth |
| CGA | Common Ground Architecture |
| CONOPS | Concept of Operations |
| COTS | Commercial Off-the-Shelf |
| dB | Decibels |
| DoS | Denial of Service |
| EL | Elevation |
| EPO | Emergency Power Off |
| ESA | European Space Agency |
| GB | Giga-Byte |
| GENSO | Global Educational Network for Satellite Operations |
| GHz | Giga-Hertz |
| GOTS | Government Off-the-Shelf |
| GPS | Global Positioning System |
| GSS | Ground Station Server |
| IP | Internet Protocol |
| IPSec | Internet Protocol Security |
| ISS | International Space Station |
| kbps | kilobits per second |
| L2TP | Layer 2 Tunneling Protocol |
| LEO | Low Earth Orbit |
| LNA | Low Noise Amplifier |
| MC3 | Mobile CubeSat Command and Control |
| MCC | Mission Control Client |
| NPS | Naval Postgraduate School |
| NPSCul | Naval Postgraduate School CubeSat Launcher |
| NRL | Naval Research Laboratory |

| | |
|---|---|
| NRO | National Reconnaissance Office |
| QoS | Quality of Service |
| OUTSat | Operationally Unique Technologies Satellite |
| P-POD | CalPoly Picosatellite Orbital Deployer |
| PPTP | Point to Point Tunneling Protocol |
| RF | Radio Frequency |
| SOC | Satellite Operations Center |
| SGSS | Space Ground System Solutions |
| SSL | Secure Sockets Layer |
| UPS | Uninterruptable Power Supply |
| USB | Universal Serial Bus |
| VAC | Voltage Alternating Current |
| VDC | Voltage Direct Current |
| VPN | Virtual Private Network |

# I. INTRODUCTION

## A. SPACE EDUCATION

CubeSats are small, often cubical, satellites designed to lower the cost and increase the availability of getting a payload into space. The CubeSat program combines a basic satellite bus standard, a standard deployment system, and a common interface with a wide variety of international launch platforms. Over 60 academic programs, ranging from high schools to graduate programs, use CubeSats to further their educational opportunities [1].

The use of CubeSats and the further refinement of CubeSat standards will continue to provide numerous educational opportunities at all educational levels and throughout several disciplines. From the hardcore engineering of subsystems down to the an individual component, to the operational art of matching limited resources with tight deadlines, from verifying compliance with government regulations, to informing the public to the benefits of specific space missions and inspiring the next generation of scientists, engineers, and thinkers, the CubeSat community has a fantastic opportunity to accomplish those goals and more.

The National Resonance Office's (NRO) Colony program is designed to take advantage of the CubeSat simplicity to quickly get new technology into space and reduce the risk and cost of testing new technologies and operational concepts and ideas. By reaching out to universities, service academies, and government labs the Colony program stands ready to capitalize on the best ideas from a wide variety of sources [2]. To reach this goal the Colony II program combines a common satellite bus with open payload space and the Mobile CubeSat Command and Control (MC3) ground station. The Colony II program is a great opportunity to enable the CubeSat community to blend research and educational opportunities with funded projects supporting national goals that may help American space operations today and in the future.

### 1. CubeSats and SmallSats

The CubeSat community hosts two workshops every year. California Polytechnic State University hosts the spring workshop at its San Luis Obispo Campus. The spring 2011 conference brought over 50 presenters from high schools, American and International universities, industry, and government agencies together to share what their hard work, ideas, and equipment could contribute to the CubeSat community.

The summer CubeSat workshop the weekend before the August SmallSat conference is hosted by Utah State University in Logan, Utah. The CubeSat weekend starts with presenters updating the CubeSat community on their latest progress. Although the CubeSat conference concludes on Sunday, the big draw starts on Monday with the SmallSat conference. The SmallSat conference draws everyone that works with small satellites. The biggest names in space like SpaceX, NASA, L3, Ball Aerospace, and the Air Force present on the same floor as major CubeSat suppliers like Pumpkin, Clyde Space, and GomSpace which share exhibition booths with students from top universities around the world. The week of presenters include everyone from SmallSat sponsors, such as the NRO, NRL, and NASA, to CubeSat design and operations teams presenting their view of the future and their triumphs and failures with CubeSats [2].

### 2. Colony II, MC3, and NPS

During the 2011 SmallSat Conference keynote address NRO director Bruce Carlson endorsed the Colony II program as a way to give experimental payloads and new parts space heritage in a way that is cost-effective and does not interfere with current missions. The NRO commitment to the Colony II program is currently manifested in the purchase of twenty [3] Colony II satellite buses and six MC3 ground stations [4]. As of September 2011, the first batch of Colony II satellite buses are slated for distribution to various universities and laboratories for experimental payload integration. The contract with Boeing is written to permit procurement of an additional 30 Colony II buses [3]. There are currently no other funded programs that have such a large number of satellite buses available and provides distributed ground station support.

The original MC3 is the ground station that supported Colony I missions and when updated will support Colony II missions. The MC3 ground station uses Commercial Off-the-Shelf (COTS) equipment tied together with Government Off-the-Shelf (GOTS) software to provide a low-cost, easy to operate ground station specifically designed to support the Colony II satellite bus. The system uses the Common Ground Architecture (CGA) software. The MC3 allows the satellite communications systems to be tested on the same equipment it will use to operate, using the same commands, radios, and antennas. Once deployed, the world-wide network of MC3s will provide coverage at geographically advantageous areas to universities, service academies, and research facilities who operate Colony II satellites. The MC3 comes in one computer rack and uses two portable antennas for easy installation at any participating facility. Figures 1 and 2 show the Colony I MC3 computer rack and one of the antenna masts.

Figure 1. Colony I MC3 Rack (From [5])

Figure 2. Colony I Antenna (From [5])

NPS involvement with the Colony program started with the introduction of the Colony II satellite bus and MC3 ground station. NPS was approached by the NRO CubeSat Program Office to build, test, and host an MC3 ground station and act as the master, coordinating node for all MC3s installed at universities. At the same time, NPS is also collaborating with Lawrence Livermore National Laboratories in the use of the Colony II satellite bus for integration and operation of space based, situational awareness satellites for tracking other satellites and space debris. These Colony II satellites are currently manifested for flight on the NPS CubeSat Launcher (NPSCul). NPSCul takes eight Cal Poly Picosatellite Orbital Deployers (P-PODs), binds them into one unit, and attaches as an auxiliary payload on a launch vehicle. NPSCul is scheduled for launch as part of the OUTSat (Operationally Unique Technologies Satellite) on NRO launch 36 in mid-2012.

## B. ASSEMBLY, SETUP, AND WIRING GUIDE

In an attempt to get a head start on operating the MC3 by possibly listening to currently operating CubeSats and other amateur satellites (AMSATS), assembly of the MC3 was started as soon as parts arrived. This was a problem since not all the parts were on hand and the final parts list was still in development. Trying to assemble an MC3 in the order in which the parts arrive is an exercise in futility. It is much better to wait until all the parts arrive and then put the MC3 together. When assembling pieces and parts as they arrive, parts were installed then uninstalled just to be reinstalled later as components that shipped quickly always seemed to block the installation of the later arriving parts.

Appendix B is a list of additional tools used to assemble the MC3. All of tools are common in shop environment but if building an MC3 from scratch these tools are the minimum required to assemble the MC3. Specific assembly instructions for the parts on hand to work with are found in Appendix C through V. The appendices are best worked through in order. As a rule of thumb, it is best to install all the hardware in the rack before connecting power and data cables.

The pictures presented are to better illustrate the techniques, instructions, and components in each step. The pictures were taken as parts arrived and were installed in the MC3 rack. Some pictures were taken in the final, installed state while others were staged on the desk or the floor to better illustrate a specific step. Pictures are included to highlight specific steps, regardless of whether the background in a given picture matches the current configuration of the MC3.

The lessons learned for each component are presented when the component is first mentioned in the guide. The lessons learned try to encapsulate the hands-on knowhow in making the parts work as a system that is not in the user's manuals, warranty information and other errata provided by the manufacturers. The lessons learned provided in Chapter III provide insight that comes in handy when assembling an MC3. Have Chapter III handy when working through the Appendices and assembling an MC3.

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# II. DISTRIBUTED GROUND STATION EDUCATIONAL OPPORTUNITIES

## A. COLONY I AND MC3

Colony I was the Naval Research Laboratory's (NRL) first attempt at using CubeSats to send, receive, store, and forward data to meet current operational needs. Their Colony I mission was a proof-of-concept to use CubeSats as technology demonstrators and remote, automated, and COTS and GOTS based ground stations to complete the mission [5]. NRL sought to use the low cost and shorter development and testing timelines associated with a simple, single mission satellite to test its radio payload. Single mission CubeSats have a huge advantage over their more complicated, multi-mission counterparts, the CubeSat is ready to launch once its single experiment is integrated and tested, whereas multi-mission satellites must wait until all experiments and sub-systems are fully integrated and tested.

### 1. Hardware and Software

The NRL Colony I satellites, designated QbX 1 and 2, were based on the Pumpkin XS-25a CubeSat bus. The XS-25a provides a 3-axis stabilized platform, hinged, deployable solar panels with a Clyde Space electrical power and battery storage system, flight control software, and a payload bay. The payload consisted of an extendible antenna, a modem, and radio. The QbX satellites are complex enough to thoroughly test ground station command and control.

The Colony I MC3 consisted primarily of COTS hardware ordered from common amateur radio suppliers like Yaesu, M2 antennas, and ICOM radios. The heart of the Colony I MC3 was the CGA laptop controlling the ground station. The CGA software controls all aspects of the ground station and satellite operations. During the development and testing of the Colony I satellite the MC3 ground station hardware and CGA software were used to control, test, and develop the satellite operating system. CGA allows for the development of flight hardware on actual ground station hardware using the same commands, data paths, and operations as the satellite would use once on orbit. By using the same hardware and software for development, testing, and operations, risks associated with using different test gear from actual flight gear are eliminated because the hardware and software do not change from development to flight. For communicating with a satellite, CGA takes the ephemeris data of the tracked satellite, tunes the radios to the appropriate frequencies, aligns the antenna to track the satellite during the pass, transmits all queued commands, and receives all data from the satellite. CGA forwards the data to any desired recipient and alerts engineers if the satellite is not operating at expected levels. With proper programming CGA could even analyze bus and payload data. When properly configured a MC3 ground station can operate completely unmanned; if there are any problems that normal troubleshooting procedures cannot solve, the MC3 will e-mail, text, and phone support engineers to alert them to the trouble. The virtual private network (VPN) between the two ground stations provide a secure, encrypted link for the seamless transfer of data and commands [4]. The Colony I MC3 block diagram is shown in Figure 3. The QbX is shown in Figure 4.

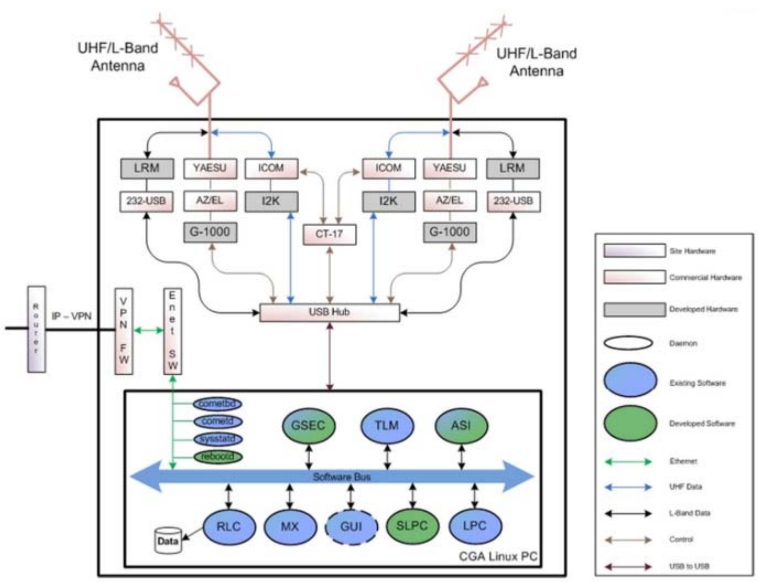


Figure 3. Colony I MC3 Configuration (From [5])

Figure 4. QbX Satellite (From [5])

### 2. Operations

The mission was controlled from the Satellite Operations Center (SOC) at Blossom Point using the ground stations in Melbourne, Florida, and Fort Huachuca, Arizona. The mission tested sending information from remote sensors to users via the QbXs to the Colony I MC3 to the Internet. The CGA implementation in MC3 allowed for the ground stations to be unmanned 24/7 and only signal for assistance if a ground engineer was needed to resolve a problem [5]. The Colony I basic architecture and operational diagram is shown in Figure 5.

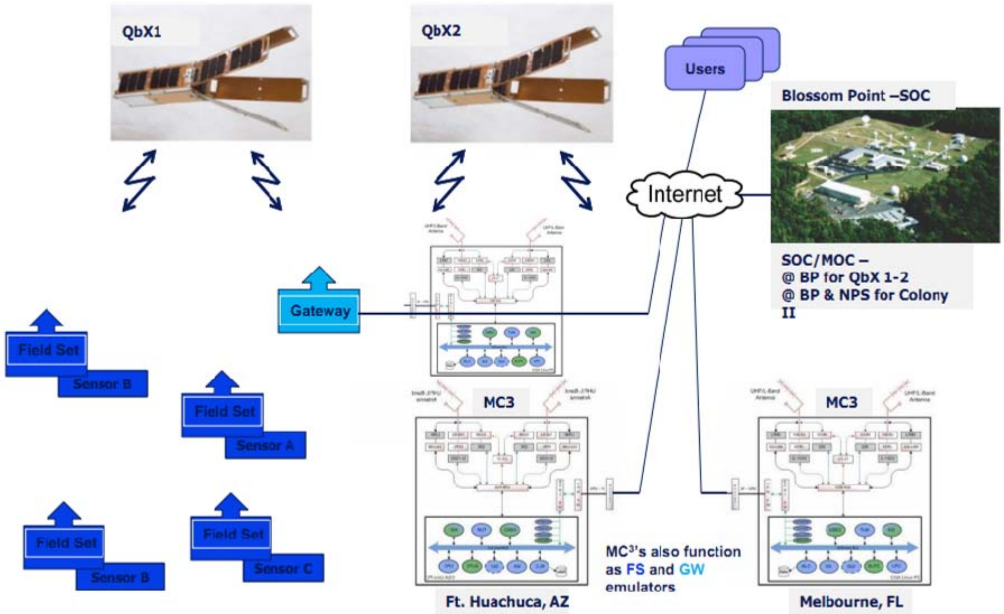


Figure 5. Colony I MC3 Operational Diagram (From [5])

### 3. Educational Opportunities

Colony I was a successful mission that proved the concept of building CubeSats, testing them, and then flying them in a short amount of time. The program provided insight and operational experience about satellite design, CubeSat ride share problems and operations, and on-orbit CubeSat operations. Some specific lessons from the QbX mission include how to use SpaceX deployment data to start the search for the QbXs and the difficulty and time required to determine which CubeSats were the QbXs in the cloud of CubeSats released from multiple P-PODs [5]. The original Colony I production run provided 12 buses for experimentation and development. Additional study and academic deconstruction of the QbX mission might yield some additional lessons learned; however with the larger production run of 20 Colony II satellite buses, there are continuing flight opportunities in the Colony II program.

## B. COLONY II AND MC3

NRO Director Carlson stated in his SmallSat 2011 Keynote address that CubeSats are an important part of the technology demonstration to transition new ideas from cutting edge to flight legacy status. The NRO has contracted Boeing to build 20 Colony II buses with the option to expand the order to 50. The Colony II program is funded, has started delivering products, and is currently programmed to have support for FY12.

### 1. Hardware and Software

Building on the knowledge gained from the Colony I MC3, the improved Colony II MC3 combines time tested equipment with cutting edge radios to enhance the data transfer capability. The new ICOM 9100 radio was approved for use by the FCC in January 2011. The S-Band GDP receiver was custom built for the Colony II MC3 [6].

CGA is still the core of the MC3 network. Once the initial setup of mission parameters, such as orbital elements and radio frequencies, is complete, it allows for automated data collection of numerous Colony II satellites without continuous user interaction. The downloaded satellite data can also be delivered to the mission owner, again without any user interaction. The Colony II MC3 hardware block diagram is shown in Figure 6.

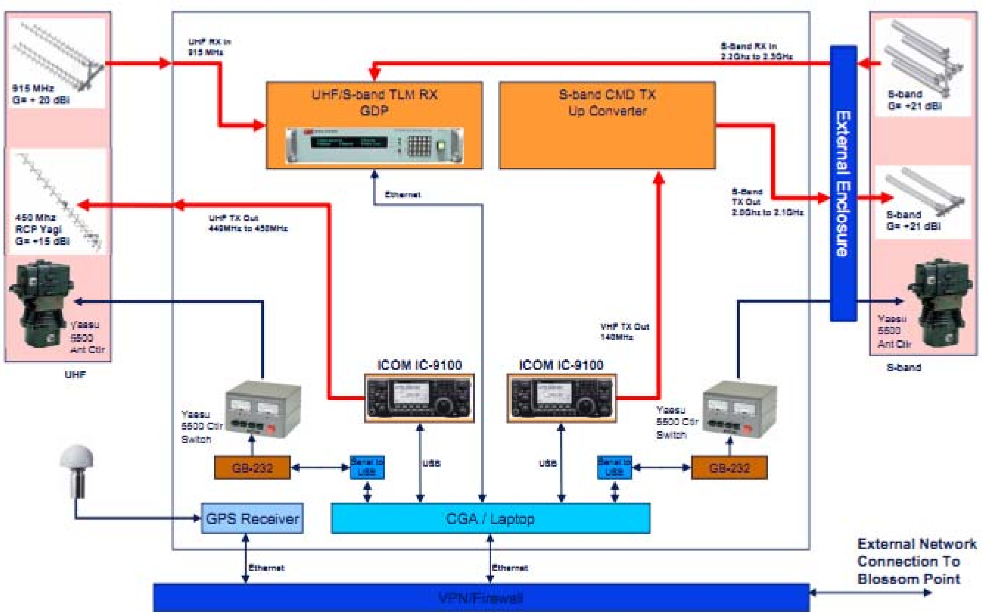


Figure 6. Colony II MC3 Configuration (From [6])

### 2. Operations

Colony II operations also expand on the foundation of Colony I. The original Colony I MC3s have been upgraded to meet the Colony II requirements and will be redeployed to provide coverage in Florida and an additional installation in Guam. These MC3s will support missions operated from the SOC at Blossom Point [6].

NPS will host the central node of educational MC3s distributed to universities participating in the Colony II program. Currently planned university nodes include Utah State University, University of Hawaii, University of Alaska, and Air Force Institute of Technology (AFIT). These installation locations are subject to change as mission parameters change and launch dates for university specific Colony II satellites change [6].

Figure 7 shows how both the NPS-centric and Blossom Point-centric networks will work together to guarantee that NRO will gather the data it desires from the Colony II program while universities will gain the data their students, staff, and satellite operators need to complete their missions.

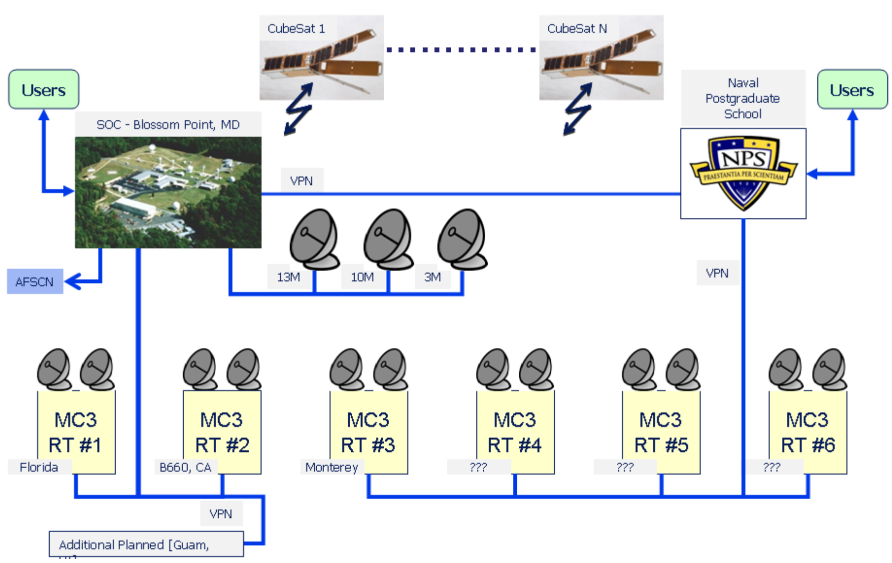


Figure 7. Colony II MC3 Operational Diagram (From [6])

### 3. Educational Opportunities

The current Colony II MC3 plan will build on the successful testing, launch, operation, and deorbit of QbX. Taking a tested ground station setup, upgrading it, and making it available to the Colony II satellites will provide all participants with the opportunity to focus on what it takes to ready a payload for space flight and how to operate it on-orbit. Using a common ground station architecture and a common satellite bus will allow Colony II participants to share experiences during the building, qualifying, and operational phases of their satellites. The MC3 ground architecture and increased opportunities for launches should maximize the opportunity for Colony II satellites to get into space and accomplish their mission.

Using a common satellite bus minimizes the initial bus design investment by giving all participants a working baseline. During the payload integration and testing, each satellite team will need to understand and operate the bus subsystems along with the payload to ensure the integrated satellite is ready for operations in space. This will allow the teams to spend their time developing the payload and planning the mission rather than troubleshooting satellite bus issues. Using a common ground station with CGA software, initial design troubles can be avoided by using proven and tested equipment. The personnel operating the ground station can focus on satellite control and data analysis instead of developing and troubleshooting their own ground station.

## C. GENSO

The Global Educational Network for Satellite Operations (GENSO) is an ambitious collaboration between the European Space Agency (ESA), educational institutions, and amateur radio operators, around whose goal is to establish a worldwide network to provide the ground segment support for educational small satellite missions [7]. The ground station architectural goals of GENSO are similar to Colony II's ground station goals of providing a world-wide network of ground stations with similar, standardized hardware to support CubeSat operations.

### 1. Hardware and Software

GENSO software is written in Java to provide flexibility and independence from computer hardware. Currently, drivers for popular ground station hardware are written, tested and operational. The supported hardware includes the Yaesu G-5500 and GS-232 rotor controller and computer interface, also used with MC3 [8]. The ICOM 910, the radio also used in the Colony I MC3, is the radio of choice for a GENSO ground station. Templates for drivers of additional hardware are available from GENSO if ground stations do not have currently supported hardware installed.

Computer requirements are modest: a 1 GHz processor, 1 GB of RAM, 1 GB of hard disk space and a 256 kbps Internet connection. GENSO only supports X.25 data packets in its Radio Frequency (RF) equipment. There are no plans to support IP packets or other forms of data via radio [8].

### 2. Operations

GENSO operates on a client/server model. The Authentication Server (AUS) is the master control node for all GENSO operations and is physically located at the University of Vigo, Spain. The AUS authenticates all ground station hardware sites acting as a Ground Station Server (GSS) node and all satellite operation centers running Mission Control Client (MCC) nodes when they log on to the GENSO network. The AUS verifies, plans, and assigns GSS resources for all MCC access requests. The AUS verifies and transfers all commands and data between the MCC and the GSS [7]. The GENSO concept of operations (CONOPS) is shown in Figure 8.

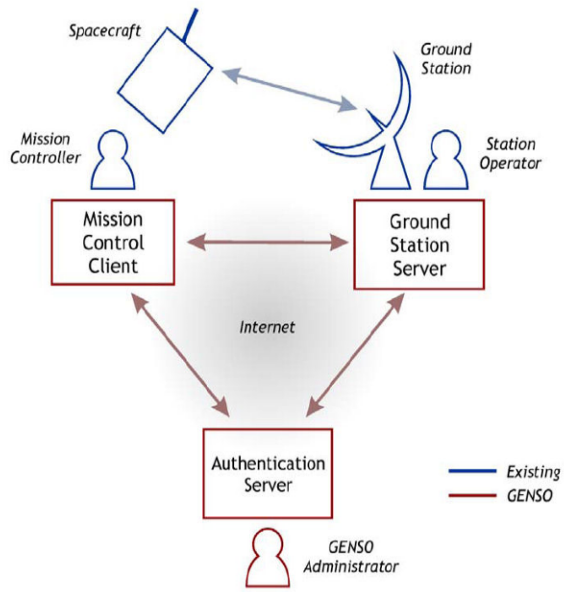


Figure 8. GENSO Operational Diagram (From [7])

GSS nodes control the actual ground station hardware. The GSS computer must be powered on, along with the attached radio equipment, and logged in to the GENSO network in order to contribute to the GENSO program. When connected to the GENSO network, the GSS accepts orders from the AUS. The AUS can give preference to the ground station owner's satellite, if desired. Since the GSS radios transmit to satellites, if required, the GSS owner is responsible for complying with all radio licensing and transmission laws in the jurisdiction where transmitting [7].

MCC nodes allow spacecraft operators to operate their spacecraft. The MCC node controls operations, formats all commands and receives all the data from the mission. All requests for data transfers originate at the MCC, are passed to the AUS and are executed by the GSS [7].

GENSO allows satellite operators to use the MCC to issue commands worldwide, while the AUS schedules and de-conflicts satellite passes and orders the GSS to carry out the mission. The planned GENSO ground station network is shown in Figure 9.

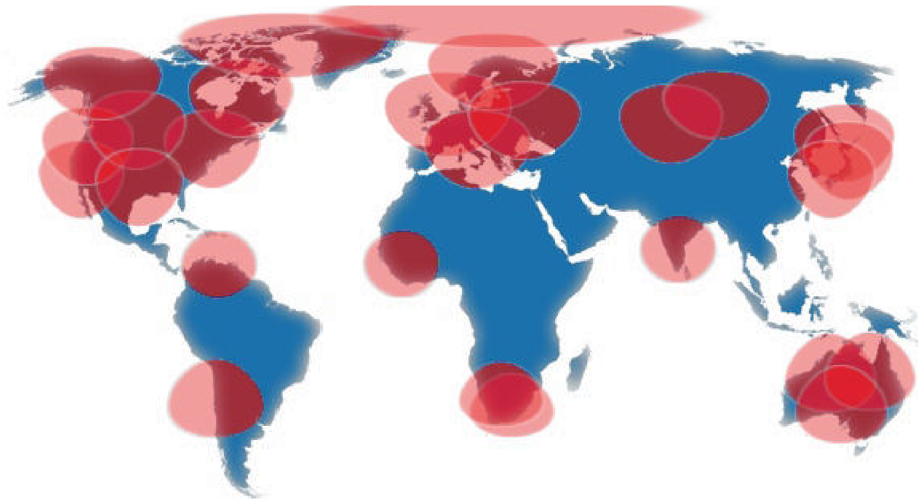

Figure 9. GESNO Planned Ground Station Locations (From [7])

### 3. Educational Opportunities

GENSO provides a wonderful educational opportunity for students learning satellite program management and operations. Free access to radio hardware around the world via GSS, free MCC software, and the low cost of a GENSO compatible computer make the ground segment of a space mission very cost effective; this frees up money for the spacecraft development, testing, and acquisition. Combined with a separate ride-share program to limit the launch costs and the CubeSat form factor and standardized launchers such as the P-Pod and NPSCul, GENSO provides a great way to lower the costs of educational space.

# III. MC3 COMPONENTS

The MC3 rack houses the majority of the equipment required for the ground station. Here the computer running CGA connects with the radios, the antenna rotor controllers, network devices, and the GPS timeserver to keep everything synchronized. The antennas, rotors, and amplifiers and filters that need to be physically close to the antenna to reduce noise and maximize the signal gain are the only components not housed in the rack. Figure 10 shows a CAD representation of a completed MC3 rack.

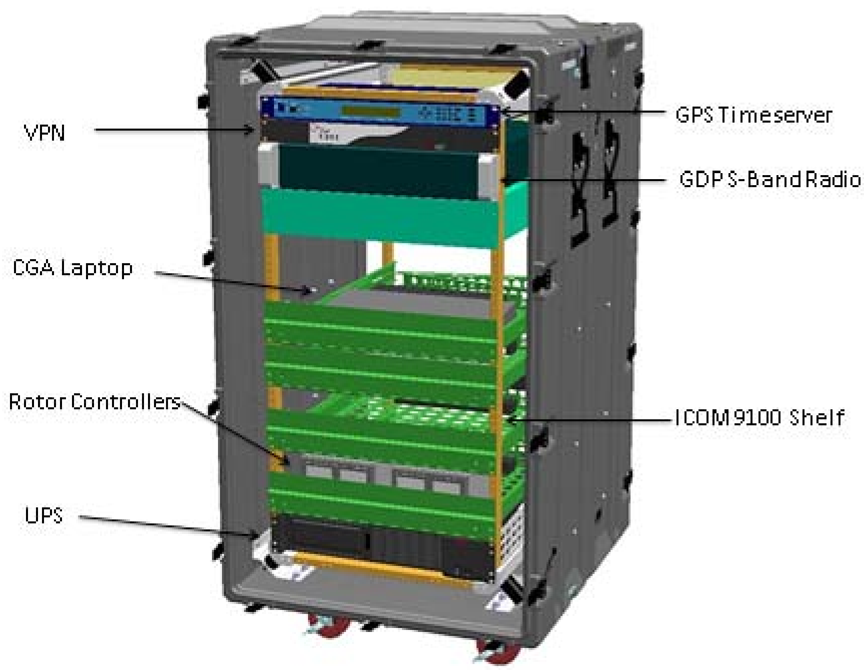


Figure 10. CAD Representation of the MC3 (From [6])

## A. HARDIGG RACK

The Hardigg REST21UDE case provides 21 U of space for the Colony II MC3. Colony I's MC3 used the smaller 14 U rack. A rack U is 1.75" tall. Rack U measurements are not to be confused with the 10x10x10 cm dimensions of a CubeSat U. The rack houses the main components to the MC3. The hard plastic shell and wheels put the mobile in MC3. While an MC3 is not designed to be used, literally, on the move, having a rack that doubles as a shipping container makes for easy storage, shipment, and use without additional packaging and installation costs. Figure 11 shows the empty Hardigg case.

Figure 11. Hardigg REST21UDE MC3 Case

### 1. Lesson Learned

Marking the U addresses before installing other hardware will make alignment and installation easier in later steps. The first attempt to install equipment without labeling each U caused rework to solve the alignment problems. Installing the 1 U shelf with its 2 U cover seemed like a good alignment scheme. Rework was required when it was realized that the ICOM radio equipment needed 3 U of rack space, resulting in the removal of two shelves. Having the actual U addresses from the start would have prevented this rework.

The NPS rack came without brackets on the side to mount the detachable covers. Without the brackets, the front and rear covers now live in a corner and are often in the way of other equipment. When ordering the rack, make sure the rack has the brackets so the covers can always be stored on the rack.

## B. UPS

The APC Smart-UPS RT-1500 provides for continuous 120 VAC (Voltage Alternating Current) power to prevent brownouts, sags, and surges in power and minimize the effects of a loss of commercial power by allowing for a graceful shutdown of MC3 hardware [9]. The Uninterruptable Power Supply (UPS) provides conditioned power to all MC3 equipment in the equipment rack. Continuity of power is important to sensitive electronic equipment minimizing the chance of damage due to power fluctuations and improper voltage. The UPS is shown in Figure 12.

Figure 12. APC RT-1500 UPS (From [9])

### 1. Lessons Learned

The UPS is best installed first since it is heavy and goes at the bottom of the rack; it should be plugged into the wall last. The UPS is the only MC3 component in the case that requires an external power cable. While the power cable is long and allows for easy placement of the MC3 rack in any environment, the cable also acts as a leash to the rack. When installing other components, a plugged in power cable can limit the movement of the MC3, present a trip hazard to the personnel, and can get in the way of other components. It is best to coil the cable under the UPS and plug it in at the end.

## C. SLIDING RACK SHELVES

The Innovation First sliding laptop shelves are used to hold not only the laptop but also the two ICOM 9100 radios and the Yaesu rotor controller equipment. The 2 U faceplates are used on all four shelves. The two lower racks used for the radio require special modification of the tie-down tabs to allow the radios and power supplies to fit on the shelf. A cutaway view of the sliding rack shelf is shown in Figure 13.

Figure 13. Sliding Rack Shelf (From [10])

### 1. Lessons Learned

Initially, the cotter pins were fully inserted so that the round top secured the hinge pins in place. This resulted in the cotter pins hanging straight down and rubbing on equipment in close proximity to the bottom of the shelf like the top UPS and the tops of the radios and power supplies. Figure 14 shows the double captured cotter pin that can drag on equipment mounted below.

Figure 14. Double Captured, Dragging Cotter Pin

The initial attempt to solve this problem was to only insert the cotter pin half-way so the cotter pin stayed flat against the hinge pin. While this solution worked in the short term, each pin was just one bump away from either coming undone or sliding into the round top and rubbing on the equipment. Figure 15 shows the single captured cotter pin.

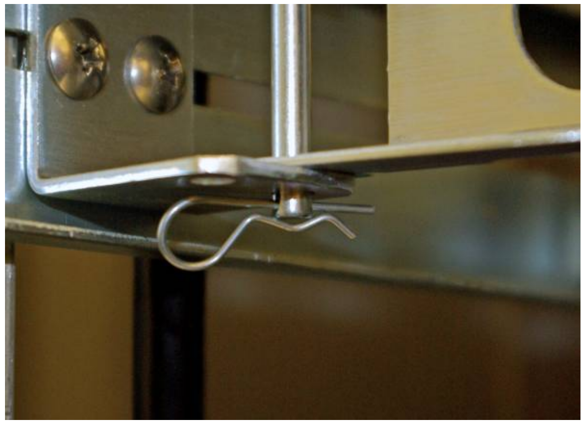

Figure 15. Single Captured Cotter Pin

A better solution is to fully insert the cotter pin and then tape the pin to a wire guide arm. This solution uses the full holding power of the cotter pin and prevents it from rubbing on other equipment. Figure 16 shows the double captured and taped cotter pin.

Figure 16. Double Captured, Taped Cotter Pin

The Innovation First sliding laptop shelves are quite fickle. The telescoping arms have several locking mechanisms to prevent the shelf from being pushed in an askew manner. Like most shelves, the Innovation First shelves have pull-tabs on the telescoping arms to prevent unwanted closure of the shelf when not pulling on the tabs. Unlike other shelves the pull-tabs on the Innovation First shelves do not actually work. Once fully extracted the shelves stay locked out even when pulling on the tabs. To close the shelf, a tool like a small screwdriver or fingernail is needed to override the locks and close the shelf. Future MC3 units should use different shelves.

## D. GPS TIMESERVER

The Symmetricom SyncServer S250 provides precise time services based on the Global Positioning System (GPS) constellation. Precise timing services are necessary to synchronize VPN encryption, properly calculate Doppler shift for maintaining satellite radio contact for the duration of a satellite pass, and for properly reconstructing data packets not received in order. Having this local time server gives each MC3 ground station access to the highest quality, stratum 1 GPS time services. Backup stratum 2 services from the S250's local Rubidium oscillator are used if GPS time services are not available [11]. If GPS time is lost the stratum 2 services provide accurate time, for computer synchronization purposes, for at least seven days of continuous communications before the system needs to resynchronize frames [12]. The GPS timeserver is shown in Figure 17.


Figure 17. Symmetricon SyncServer S250i (From [11])

### 1. Lessons Learned

The 75 ohm BNC-BNC cable that connects the S250 to the rear faceplate is not on the parts list nor are the BNC connectors and cable required to make one. This cable needs to be added to the parts list.

When testing the GPS timeserver, the GPS antenna was connected directly to the GPS timeserver with the antenna placed in a window. A short time later the GPS timeserver was receiving valid time signals from three GPS satellites. No further operational tests of the unit were conducted.

## E. NETWORK SWITCH

The Netgear ProSafe 24 Port GS724T provides network switching services for all components in the MC3. The network switch provides advanced features including access control list (ACL) filtering for whitelist and blacklist security, QoS services, and also operates well as an unmanaged switch. The current MC3 configuration does not make use of any of these advanced features. If the MC3 network were to need to implement ACLs for additional security or QoS for bandwidth management, those features can be implemented without an additional hardware purchase. The network switch is the heart of network connectivity [13]. The network switch is shown in Figure 18.

Figure 18. Netgear GS724 ProSafe 24 Port Switch (From [13])

### 1. Lessons Learned

The original Colony I MC3 used a 16-port switch. In an effort to save money, the same 16-port switch was called for in Colony II MC3s; however, Netgear stopped production on the original 16-port switch. The GS724T model replaced the old 16-port switch in the Netgear product lineup and in the MC3. There is no operational change since only 4 ports in the switch are used.

## F. POWER DISTRIBUTION UNIT

The CyberPower CPS-1215 RM rack mounted power tap provides ten, 120 VAC plug receptacles in a 1 U configuration [14]. The Power Tap is installed at the 9 U location on the rear plane of the rack. This is directly below the Netgear Switch location. This location allows the inward-facing plugs and cables to extend freely up and down the body of the case without binding on any of the sliding shelves or other equipment. Figure 19 shows the front and back of the power distribution unit.

Figure 19. CyberPower CPS-1215 RM Power Distribution Unit (From [14])

### 1. Lessons Learned

Early designs called for several COTS power strips on every sliding rack shelf to distribute power for all MC3 equipment. This power distribution unit removed the power strip from three of the four shelves and made for a much cleaner way to run power to rack mounted equipment. The power distribution unit is a great upgrade from the original requirement of a power strip on every shelf.

## G. VPN

The Swift Systems GTA800e VPN provides a full suite of network monitoring, management, and protection services. Protective services include firewall, intrusion detection, Denial of Service (DoS) prevention, mail filtering and anti-spam services, anti-virus scans, and content filtering. The DoS features will help keep the MC3s available for Colony II use and will minimize the exposure to Internet attacks. The anti-spam and anti-virus features will help keep individual MC3s safe even if a particular MC3 is infected or compromised. The VPN supports numerous security protocols for encrypted VPN connections, hardware acceleration, and connection management [15]. In the MC3 the VPN provides various ways to establish secure, encrypted connection between other

MC3 sites to pass data and commands between users no matter where they are physically located. The VPN is shown in Figure 20.

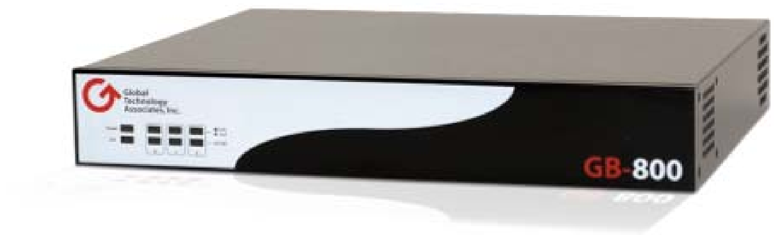


Figure 20. GTA 800e VPN (From [15])

### 1. Lessons Learned

Production of the Swift Systems GTA800e VPN was discontinued after the MC3 parts were ordered for this study; however, it is still supported by Swift Systems. The replacement system, GB-820, is available for purchase and offers similar services as the GTA800e. The most noticeable change with the new GB-820 is that it has four RJ-45 Ethernet ports vice the GTA800e‘s three ports. Since the MC3 only uses two ports, the GB-820 should be a suitable replacement for the GTA800e if further MC3s are built.

## H. IC-9100 UHF RADIO

The IC-9100 combines HF, VHF, and UHF transceivers in one unit. The unit supports satellite operations by synchronizing the uplink and downlink frequencies and compensating for Doppler shift during the satellite pass [16]. The IC-9100 replaces the IC-910H used in the Colony I MC3. Since the creation of the Colony I, the IC-910H has been discontinued and is replaced with the IC-9100. The discontinued IC-910H required an additional controller to that interfaced between the radio and an RS-232 serial port on a computer. The new IC-9100 simplifies the MC3 and uses a USB (Universal Serial Bus) connection for computer control. While it supports multiple amateur modes of radio operations the MC3 only uses it for 450 MHz uplink and 915 MHz downlink. The Cross Technologies block up-converter is used to convert the 915 MHz downlink into a frequency handled by the IC-9100. The IC-9100 is shown in Figure 21 and the power supply is shown in Figure 22.


Figure 21. ICOM IC-9100 (From [16])


Figure 22. ICOM PS-126 (From [16])

## I. G-5500 ROTOR CONTROLLER

The Yaesu G-5500 Elevation-Azimuth Dual Controller is specially designed for satellite communication applications. The rotor features 450º of azimuth control and 180º of elevation control [17]. The Colony I MC3 successfully used the G-5500 and GENSO drivers are already written, tested, and available. The G-5500 is a proven stalwart in amateur satellite communications equipment. The G-5500 rotor controller and rotor are shown in Figure 23.


Figure 23. Yaesu G-5500 Rotor and Controller (From [17])

### 1. Lessons Learned

The G-5500 comes with a bright red power switch, but the switch gives no indication as to on or off status. In a bright environment, it is not easy to see the faint glow of the AL/EL gauge backlight. To eliminate the problem for new users in telling if the unit is on or off, additional markings were added to the G-5500 face. Figure 24 shows the ON and OFF indication upgrade.


Figure 24. G-5500 – With ON and OFF Labels

The 6-wire AL/EL connections need some sort of tip protection. When attempting to install bare wire, the twisting and clamping motion of the screw caused the wires to fray and come in contact with other terminals. Soldering the connections prevented the fraying.

The other G-5500 controller at NPS has used solder-less connectors. The connectors work well and require much less training and practice than is required to properly solder the tips of the wires in a curve. For future G-5500 installations, using solder-less connectors is recommended because of their ease of use and clean installation.

The plastic covers removed from the connector face of the G-5500 are not reinstalled in the above instructions. However, they may be reinstalled if desired.

## J. YAESU GS-232B

The Yaesu GS-232B provides for computer operation of the G-5500 rotor controller via a 9-pin RS-232C connection [18]. Requests for antenna movement from the CGA software are sent to the GS-232B which commands the G-5500 to move the rotors. The Yaesu GS-232B is shown in Figure 25.


Figure 25. Yaesu GS-232B

### 1. Lessons Learned

The GS-232B comes with Velcro strips to secure the GS-232B to the G-5500. While not used in the NPS installation, the Velcro option is a good way to secure the GS-232B during shipping.

## K. ANTENNA ASSEMBLY

Two antenna masts support uplink and downlink abilities. The UHF antenna mast provides basic communication functions between the satellite and the ground stations. All Colony II satellites will have the UHF radio installed. The higher frequency S-band antenna mast provides an alternate communications path for some Colony II payloads [19].

### 1. UHF Antennas

#### *a. M2 436CP30*

The M2 Antenna Systems 436CP30 is a circularly polarized Yagi antenna for use in the 432-440 MHz range. The antennal was designed for satellite communications. The antenna features o-rings for all RF connections to increase its lifespan [20]. This is the UHF transmit antenna for Colony II satellites. Figure 26 shows a test assembly of the 436CP30 antenna. The antenna was partially disassembled for storage after the test fitting.

Figure 26. M2 436-CP30 Antenna – Test Assembly

#### *b. M2 917YA*

The M2 Antenna Systems 917YA is a polarized Yagi antenna for use in the 880-940 MHz range. The antenna features waterproof RF connections for use in harsh environments. The M2 917Y requires no user assembly for the inidividual antenna elements [21]. The four sections that make up the antenna do require specific alignment and attention to the distance between the elements to properly receive the signal. This is the UHF receive antenna for Colony II satellites. Figure 27 shows the 917Y antenna elements.

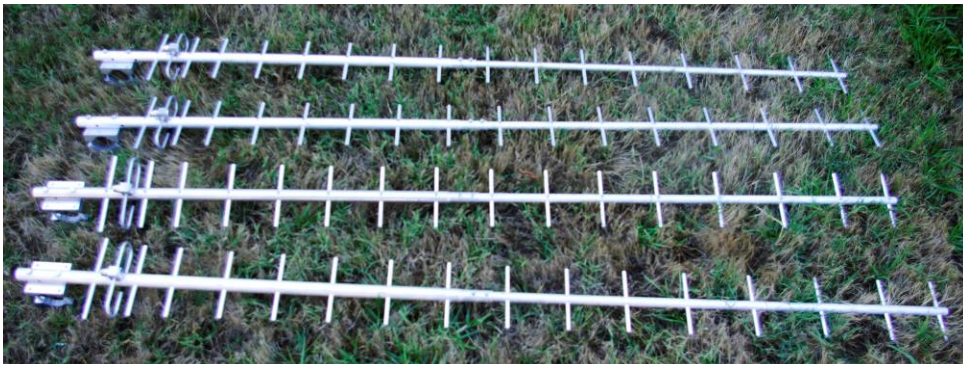

Figure 27. M2 917Y Antenna – Antenna Elements

### 2. S-Band Antennas

#### *a. M2 1975-23*

The M2 Antenna Systems 1975-23 is a Yagi antenna for use in the 1925 to 2075 MHz range. The antenna features an array of two individual antennas mounted inside a plastic shell for weather protection. The 1975-23 requires no user assembly for the individual antenna elements; however, the array must be aligned on the antenna mast [22]. Figure 28 shows the 1975-23 antenna elements.

Figure 28. M2 1975-23 – Antenna Elements

#### *b. M2 2227-21*

The M2 Antenna Systems 2227-21 is an array of four Yagi antennas in a plastic shell for use in the 2210 to 2245 MHz range. The antenna provides service for the

SGLS downlink from a Colony II satellite [23]. Figure 29 shows a test assembly of the 2227-21 antenna. The antenna was partially disassembled for storage after the test fitting.

Figure 29. M2 2227-21 – Test Assembly

## L. REAR FACEPLATE, EXTERNAL CONNECTIONS, AND EXTERNAL COMPONENTS

### 1. Lessons Learned

No screws or nuts come with the PX0767/S connectors. An additional 16 pan-head 6-40 screws, bolts, and lock washers are used to secure the connectors to the faceplate.

This is one of the few instances where signal cables are installed at the same time as the connector. Because of the six wire AL/EL cable screws in the back of the connector, installing the signal cable after the faceplate is installed would require small hands working upside-down and backward to install the signal cable later.

Wire colors in the 6-wire cable can vary depending on the manufacturer of the wire. The color of the cable is not as important as maintaining a common and consistent wiring pattern. If your wire color varies, be sure to write down the socket number to wire color combination you use.

Soldering the wire that enters the holes on the back of the connector is not required. A properly trimmed wire will leave no exposed wire outside the connector. An improper solder job could be detrimental as too much solder could prevent the wire from entering the connector.

Having tried both installing the connector in the faceplate and then installing the wiring in the connector and wiring the connector then installing the wired connector in the faceplate, the latter is much easier. Wiring the connector first cuts the installation time from 15 minutes to under 5 minutes.

Binding the four AZ/EL wires into one wire bundle before installing the faceplate is a lesson learned and will result in easier routing of the cables and less frustration in section V. The first attempt to route the four individual AZ/EL cables from the faceplate to the G-5500 resulted in a huge mess of tangled wires. Uninstalling the 24 AZ/EL connections from the back of the G-5500 was required to straighten out the mess.

# IV. MC3 LINK BUDGET AND ROTOR CONTROL

Completing an RF link between a satellite and the ground station depend on several factors. A link budget depends on the transmitter power, the gain, directional sensitivity, and pointing accuracy of the transmitter and receiver antennas, the line losses in the transmitter and receiver, and free space loss due to distance and atmospheric interference.

## A. BOEING BASELINE ANALYSIS

Boeing's Phantom Works designed the Colony II CubeSat satellite bus. Part of their design selection was the updated AstroDev UHF radio that built on the He-100 and Li-1 models. The UHF radio is designed to receive data at 450 MHz with a data rate of 9.6 kbps and transmit data at 915 MHz with a data rate of 50 kbps. The radio transmits at 2 watts and the attached antenna has a gain of 2 dB. A future option, the Colony II S-band radio is designed to receive data at 2.1 GHz with a data rate of 9.6 kbps and send data and transmit data at 2.2 GHz with a data rate of 512 kbps. The radio has a maximum transmit power of 2 watts and the attached antenna provides a gain of 3 dB [24].

While Boeing has done no work with the Colony II ground stations, their link calculations assumed a ground station with a UHF antenna gain of 14 dB and an S-band antenna gain of 28.5 dB. Based on calculations, the assumed ground station transmit power is approximately 25 Watts. The numbers used for Boeing's link analysis are shown in Figure 30 [24].

**Advanced Network & Space Systems**

Uplink

| Ground Station: *S-band 1.8m Dish (28.5dBi)* *UHF yagi type array (14dBi)* | S-Band | UHF |
|---|---|---|
| Ground Station EIRP: | 33.5 | 27.0 |
| **Uplink Path:** | | |
| Ground Station Ant Pointing Loss: | -1.0 | -0.1 |
| Antenna Polarization Losses: | -0.3 | -3.0 |
| Path Loss: | -162.4 | -148.2 |
| Atmospheric Losses: | -0.14 | -0.17 |
| Ionospheric Losses: | -0.2 | -0.2 |
| Rain Losses: | 0.0 | 0.0 |
| Isotropic Signal Level at Satellite: | -130.6 | -124.0 |
| **Spacecraft (S/C):** | | |
| S/C Antenna Pointing Loss: | -1.0 | -1.0 |
| S/C Antenna Gain: | 3.0 | 2.0 |
| S/C Transmission Line Losses: | -1.0 | -0.5 |
| S/C Effective Noise Temperature: | 616 | 597 |
| S/C Figure of Merit (G/T): | --25.9 | -26.3 |
| S/C Signal-to-Noise Power Density (S/No): | 71.1 | 77.4 |
| **Sys Desired Data Rate [kbps]:** | 9.6 | 9.6 |
| In dBHz: | 39.8 | 39.8 |
| Telemetry System Eb/No: | 31.3 | 37.5 |
| Telemetry System Required BER: | 1E-05 | 1E-05 |
| Telemetry System Required Eb/No: | 9.6 | 9.6 |
| **System Link Margin:** | **21.7** | **27.9** |

Downlink

| Spacecraft (S/C): | S-Band | UHF |
|---|---|---|
| **S/C Transmitter Power Output [W]:** | 2.0 | 2.0 |
| S/C Transmission Line Losses: | -1.5 | -0.5 |
| S/C Connector, Filter or In-Line Switch Losses: | -0.5 | -0.5 |
| S/C Antenna Gain: | 3.0 | 2.0 |
| S/C EIRP: | 4.0 | 4.0 |
| **Downlink Path:** | | |
| Spacecraft Antenna Pointing Loss: | -1.0 | -1.0 |
| Antenna Polarization Loss: | -0.3 | -3.0 |
| Path Loss: | -163.2 | -155.4 |
| Atmospheric Loss: | -0.14 | -0.17 |
| Ionospheric Loss: | -0.2 | -0.2 |
| Rain Loss: | 0.0 | 0.0 |
| Isotropic Signal Level at G.S.: | -160.9 | -156.0 |
| **Ground Station:** | | |
| G.S. Ant Pointing Loss: | -1.0 | -0.1 |
| G.S. Figure of Merit (G/T): | 6.2 | -10.6 |
| G.S. S/N Power Density (S/No): | 72.9 | 61.9 |
| **Sys Desired Data Rate [kbps]:** | 512 | 50 |
| In dBHz: | 57.1 | 47.0 |
| Telemetry System Eb/No: | 15.8 | 14.9 |
| Telemetry System Required BER: | 1E-05 | 1E-05 |
| Telemetry System Required Eb/No: | 9.6 | 9.6 |
| **System Link Margin:** | **6.2** | **5.3** |

Figure 30. Boeing Link Budget (From [24])

The Boeing results show that the UHF link margins are 27.9 dB uplink and 5.3 dB downlink. The S-band link margins are 21.7 dB uplink and 6.2 dB downlink. The large difference between the uplink and downlink margins is driven by the large difference in transmitter power between, which translates into EIRP, and the larger gain of the ground station antennas versus the smaller gain of the CubeSat antennas.

While the Path Loss entry in the Boeing calculations accounts for the free space loss due to the satellite distance from the ground station some details are missing from the analysis. The look angle between the ground station and the satellite and the orbital altitude of the satellite is not specified. A deeper understanding of the Boeing assumptions is needed to determine why the distance dependent path loss values are different for every calculation. In addition, no low noise amplifier (LNA) gains and noise figures were considered on the ground station for downlink calculations. The downlink values do not meet the 10 dB signal margin for a good link. The 10 dB minimum margin is a rule of thumb for communications. Above 10 dB of margin, and there should be no trouble maintaining the link. Below 10 dB, estimation errors for atmospheric conditions, line loss, extra RF noise in the operating environment, and other factors not accounted for, could cause enough signal loss to degrade the link and prevent data transfer. Depending on the circumstances, this could risk losing the mission.

## B. MC3 LINK ANALYSIS

To start the MC3 link analysis, an examination of the currently proposed Colony II orbits is required. One is a Sun-Synchronous orbit with an altitude of 600 km. The second is a non-circular orbit with a perigee of 480 km and an apogee of 770 km. The third is the International Space Station (ISS) Orbit, a circular orbit at approximately 385 km. The Sun-Synchronous orbit allows for an optical payload to gather consistent data over the Earth, the ISS orbit is available for CubeSats launched from the ISS, and the 480 x 770 km orbit is for a particular Colony II payload. This analysis will focus on a Colony II satellite at 770 km altitude, in a circular orbit. This is the worst-case scenario since it has the greatest free space loss during the pass. The ground station is at sea level, a good approximation for NPS and a conservative estimate for MC3 locations at higher elevations.

The Boeing data was used for all Colony II satellite radio and antenna, powers, gains, and losses. Additionally the atmospheric and ionospheric losses from the Boeing model were also used. MC3 ground station antenna gains and beamwidths were taken from M2 Antenna System documentation. The MC3 ground station uses LNAs to boost the received signal from the satellite. While LNAs-+ boost the strength of the received signal they also add some noise to the system; however the signal gain is much greater than the introduced noise. The analysis evaluated the link margin at look angles from 0 to 90 degrees. The 0-degree look angle is an extreme case that would only be possible if the ground station was on flat ground with no obstructions like trees, buildings, or surrounding mountains.

The maximum distance of the 770 km orbit is a zero look angle; this gives a total distance of 3227 km between the satellite and the ground station. The final analysis numbers show that even in this case, the current MC3 system can support two-way communications with both the UHF and S-band radios with at least a 10 dB margin. The link margin for each link is based on the different transmitter powers, transmitter antennas, receiver antennas, receiver LNAs (for downlinks), and equipment noise temperatures for each link and its associated components. Atmospheric losses, ionospheric losses, and distance losses are the same for each link condition since these factors are based on the environment and distance between the ground station and satellite. These factors are not dependent on the equipment. The LNAs were not included in the Boeing analysis, hence the significant discrepancy between the Boeing link budget and this link budget. Specifics for the 450 MHz link are in Appendix W, the 2.1 GHz link are in Appendix X, the 915 MHz link are in Appendix Y, and the 2.2 GHz link are in Appendix Z. The appendix calculations were made with the help of the NPS link budget calculator [25] and the Space Mission Analysis and Design link budget equations [26].

Figure 31 shows the link margin as a function of look angle. As expected as the look angle increases, the distance between the spacecraft to the ground station decreases, the space loss decreases, and the link margin increases.

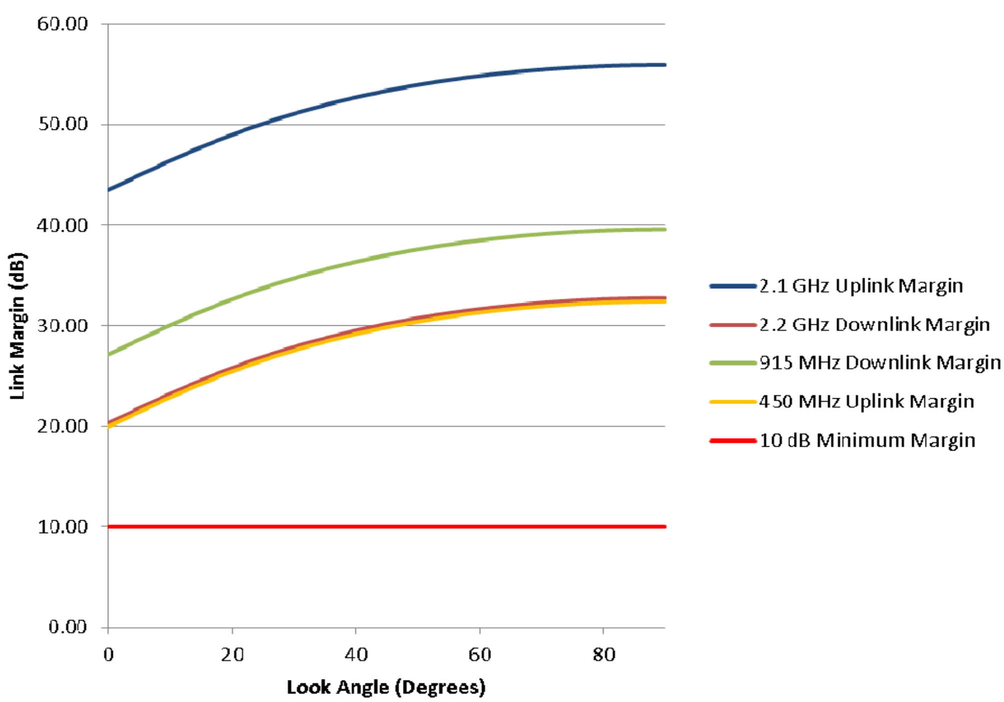


Figure 31. Link Margin and Look Angle of and MC3

The Boeing provided link analysis gives uplink margins of 27.9 dB at 450 MHz and 21.7 dB for 2.1 GHz communications. Since the MC3 uses a 50.5 dB gain, high power amplifier (HPA) for ground station S-band transmissions, the uplink margin of the MC3 at all look angles greatly exceeds the Boeing projections. Boeing's downlink analysis gave link margins of 5.3 dB at 915 MHz and 6.2 dB at 2.2 GHz. The MC3 UHF LNA provides 25.5 dB of gain and the S-band LNA provides 30.15 dB of gain thereby also exceeding the Boeing projections.

## C. ROTOR MOTION ANALYSIS

The G-5500 rotors allow an uninterrupted azimuth travel of 380 degrees and 180 degrees of elevation travel. Correctly orienting the stops and aligning the antenna with the rotors is important to ensure any satellite pass in any orbit can be collected from any MC3 ground station. One important component to completing any satellite pass is aligning 0 degrees elevation at the horizon, 90 degrees elevation straight up, and 180 degrees elevation again at the horizon. The satellite tracking software, like CGA must then be programmed to use both the 0-90 degree elevation and 90-180 degree elevation possibilities to avoid hitting the azimuth stop. Assuming a full azimuth rotation of 0-360 degrees, a system with an elevator rotor capable of only 0-90 degree movement has one unique solution to position the antenna at any azimuth and elevation. A system using an elevator rotor capable of 0-180 degree movement has two solutions to position the antenna, one using the same setup as the limited case, and one using the 90-180 degree elevation and a reciprocal azimuth bearing. Using the full 180 degrees of elevation travel allows the avoidance of the azimuth limit since the 90-180 degree elevation can point the antenna at the satellite while the rotor travels through a reciprocal azimuth of the satellite azimuth.

For the test case evaluated here, the azimuth starts at 350 degrees, runs clockwise 380 degrees to a stop at an indicated 10 degrees. The elevation will be set as described above, 0 and 180 degrees point to the horizon and 90 degrees is straight up. The satellite pass will be west to east starting at the horizon at an azimuth of 280 degrees, reaching a 20 degree look angle when due north, and setting over the horizon at 80 degrees.

If the rotor starts at an azimuth of 280 degrees, then the elevation control will run from 0 to 20 degrees to capture this pass, but the rotor will hit the azimuth stop at 10 degrees. For this case, the rotor azimuth angle is the same as the antenna pointing angle. At the start of the pass the system is pointed at 0 degrees elevation and 280 degrees azimuth. At the highest point of the pass, the system is pointed at 20 degrees elevation at due north. The pass continues until the system hits the stop at an azimuth at 10 degrees and all system motion ceases. To try to cover the end of the pass the rotor would have to unwind counterclockwise and reacquire the satellite. Depending on the satellite altitude and velocity and the rotor speed it might not be possible to reacquire the satellite before it sets over the horizon. This configuration keeps the rotor and antenna pointing in the same direction but, because it hits the rotor mechanical stop, it limits the satellite communication time. Figure 32 shows the satellite pass discussed. The look angle is in the 0 to 90 degree range.

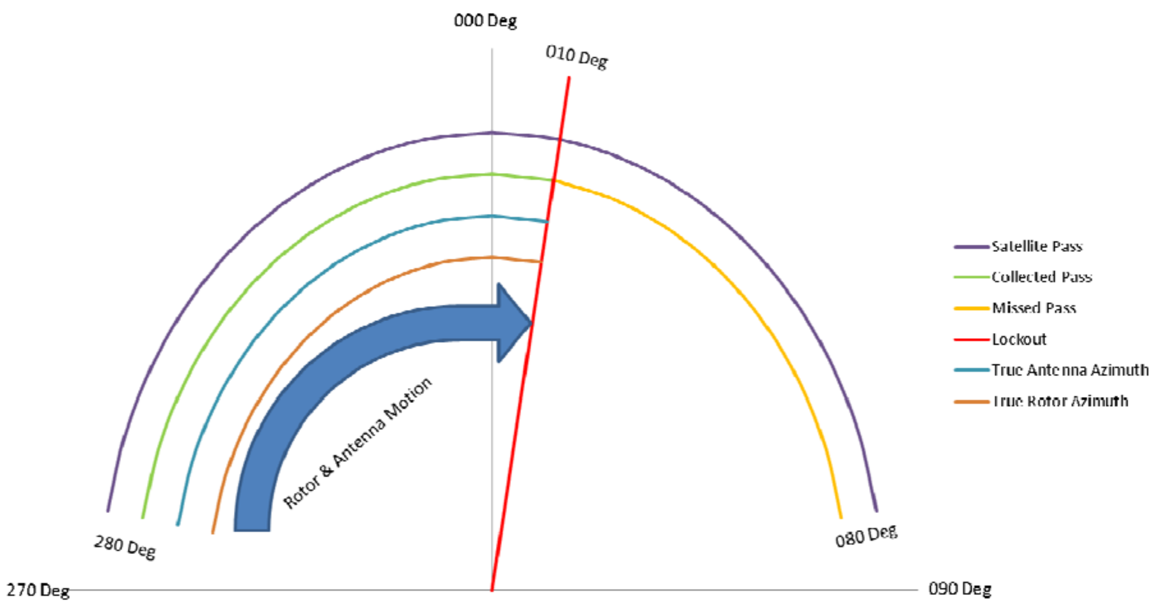


Figure 32. Antenna and Rotor Motion and Lockout Using the 0 to 90 Degree Elevation

To overcome this limitation and maximize the satellite communication time the full 180 degrees of elevation motion must be used. To continuously track the satellite through the entire pass, the azimuth rotor must start to rotate from 100 degrees azimuth and 180 degrees elevation.  At the high point of the pass the antenna will point due north, 20 degrees above the horizon, while the indicated azimuth is 180 degrees with an elevation of 160 degrees.  At the end of the pass the rotor will indicate an azimuth of 260 degrees and an elevation of 180 degrees.  Figure 33 displays the antenna and rotor motion of this preferred configuration.

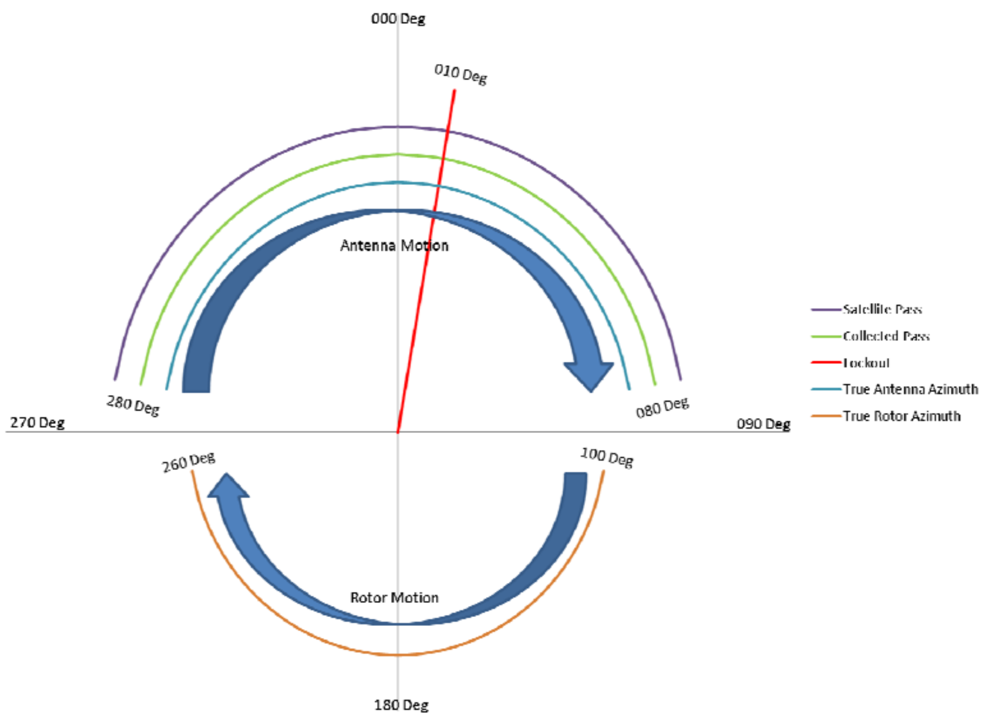


Figure 33. Antenna and Rotor Motion and Lockout Using the 180 to 160 Degree Elevation

To avoid hitting the azimuth stops, the CGA needs to be programmed with the location of the mechanical stops and an algorithm to prevent hitting a mechanical stop during a pass.  To keep the programming the same for all MC3s, all rotor installation must have their mechanical stops placed in the same location.

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# V. CONCLUSIONS AND FUTURE WORK

## A. HERE TO A WORKING MC3

### 1. GDP Space Systems S-Band Radio

The MC3 is still awaiting a functional S-Band transmitter and receiver. The GDP Space Systems 4423 is a digital RF receiver, demodulator, and bit synchronizer that contains two, independent RF paths to handle simultaneous uplink and downlink transmissions in the same box [27]. Figure 34 shows the S-Band radio powered and working.


Figure 34. GDP Space Systems – S-Band Radio (From [27])

There are two major problems with the GDP radio [28]. The Colony II S-band radio only transmits in bursts when it has a packet of data to transmit. This configuration saves power since the radio is not always transmitting, but only transmitting when data is ready. This setup is similar to a push-to-talk radio; if the operator starts speaking at the exact same time as the transmit button is pushed, the first few seconds of the speech are missed while the radios synchronize. An experienced radio operator will push the transmit button, wait a second or two, then start speaking to ensure that the message gets through. The GDP S-band radio is like an inexperienced radio operator as it transmits data before the link is completely established. While this setup saves power on the satellite, the GDP S-band radio is unable to lock on to the short signal and receive the data dependably, even in the lab environment. Until the link problem is resolved the GDP S-band radio is unusable for Colony II operations.

The second problem with the GDP S-band radio is that it does not properly translate AX.25 data packets to IP data packets. The Colony II, as well as several other CubeSats and GENSO, use AX.25 packets to encapsulate the data between the radio and the satellite. Computers on the Internet use IP data packets to route data. The conversion between AX.25 and IP is important to the distributed network operational concept of the MC3. If the MC3 is unable to translate the AX.25 packets from the S-band payload, every MC3 becomes a standalone system. Unable to share the data, the satellite mission controllers can only use the MC3 physically located at their mission control facility. Since there are over twice the Colony II users as planned ground stations, the ability to share data via the Internet is essential to the success of both the Colony II and MC3.

Once both the radio lock and data packet conversion problems are solved by GDP Space System engineers, delivery of the S-band radio can happen and further work with the MC3 can continue at NPS.

### 2. CGA Setup and Training

CGA software has been in continuous development and improvement for over 20 years. The software is written and maintained by expert computer programmers who have spent much of their career developing, operating, maintaining, and improving CGA systems.

It is difficult for users new to CGA to effectively use it on day one in its current state. Starting with a new laptop and a fresh install of CGA, it took NPS personnel several hours of failed troubleshooting to try to get CGA running. Eventually dedicated support from the lead Space Ground System Solutions (SGSS) programmer led to the restoration of CGA to the NPS desktop [29]. Specific directions are in Appendix A.

Adding additional satellite ephemeris data to CGA is not a quick and easy task. This took NPS personnel over 4 hours of telecom support with SGSS programmers and over a dozen e-mail messages with keystroke specific instructions to add one satellite to the tracking list. Once the satellite was added, it became apparent that CGA was not communicating with the G-5500 rotors.

While all data paths were properly connected, CGA and the rotor did not communicate. Once again NPS performed the best troubleshooting they could but again they were thwarted. After an additional 4 hours of conference call support with SGSS programmers and more e-mail messages with directory, file, and keystroke specific instructions the problem was resolved. CentOS and CGA do not support plug-n-play functionality of the USB-to-serial converters. Each USB-to-serial converter's unique system serial number must be added to configuration files that establish the data path between CGA and a specific GS-232 / G-5500 rotor set. Once this path is configured, the USB-to-serial converter can only work with its specific GS-232 / G-5500 rotor set.

To maximize the educational opportunities that the MC3 ground station can bring to a college program, CGA must be friendlier to use. Even with the experienced Linux programmer on staff at NPS, a significant amount of support was required from SGSS. Once the MC3 ground stations are delivered to universities across the world, it is unlikely that SGSS will have the time to provide over 5 times the help they provided NPS. Expecting SGSS to provide help to each organization with an MC3 for basic operational assistance on demand is unreasonable. Prior to the delivery of an MC3 to educational partners, NPS needs to take delivery and verify a detailed and thorough user's guide that covers the setup, operation, and troubleshooting involved with the daily operations of an MC3 ground station.

As of September 2011, once NRL has completed the three MC3s they are responsible for and shipped them to NPS, NRL and SGSS plan on spending two weeks at NPS providing direct and focused support for hardware and software installation and training. This training should take place after the MC3 systems are working properly. During the two weeks of support, it is NPS's responsibility to take the knowledge from the MC3 operators and verify the user's manual in such a way that NPS personnel can proficiently operate the MC3 network and teach other organizations how to do the same. Leveraging the student resources at NPS is a fantastic way to build operational experience in the Navy and meet the NRO objective of using Colony II satellites to demonstrate new payloads and operations in a cost effective manner.

### 3. MC3 Power Budget

The UPS provides power to MC3 components to prevent brownouts, sags, and surges in power and minimize the effects of a loss of commercial power. As of September 2011, there is no estimate to how long the UPS battery will last or exactly how the MC3 and all of its components will automatically execute a graceful shutdown in the event of an extended power outage.

To maximize the availability of the MC3 equipment during power outages, a detailed study and test of a fully functional MC3 at maximum electrical demand and its response to different power conditions needs to be completed. The study should evaluate different operating conditions, including backup time remaining under maximum load, and should evaluate controlled power down modes to extend UPS battery life.

## B. RECOMMENDATIONS FOR THE NPS GROUND STATIONS

The current NPS ground station includes an ICOM 910H radio, a G-5500 controller with a GS-232B, one mast with VHF and UHF Yagi antennas, and a three meter S-band dish. This ground station uses similar hardware to that used by the MC3s. Instead of CGA, NPS has been running Nova for Windows software. The existing NPS ground station is a stand-alone configuration with no remote sites.

### 1. MC3 – A Promising Future

The MC3 will more than double the simultaneous communications capacity at NPS. MC3 will also provide a network of similar ground stations to provide a near-worldwide ability to communicate, as a first priority, with Colony II satellites. With its wide frequency range, MC3 and its operators do not need to wait for a Colony II satellite to reach orbit to begin testing operational principles and procedures. The AMSAT community tracks over 25 satellites that amateur radio operators, educational institutions, and space enthusiasts can communicate with right now [30]. As soon as the MC3 construction and setup is completed, NPS students can use the system to gain operational experience with the hardware, software, and network environment immediately. This operational experience will ready all users of MC3 to support the Colony II mission when the first satellites reach orbit.

### 2. GENSO – Coalition of the Willing

GENSO software has not been tested nor is it currently installed on any NPS system; the evaluation of GENSO suitability at NPS is based solely on the available literature from the GENSO origination and the ESA.

While GENSO provides a wonderful opportunity for amateur radio operators, educational institutions, and space enthusiasts to pool resources and operate satellites, the GENSO network offers NPS no additional capabilities not already offered by MC3 and could be detrimental to the success of Colony II satellites.

The first problem with using GENSO to achieve Colony II's mission is the network architecture. The AUS is controlled by the faculty and students at the University of Vigo, Spain. The AUS is the central node that controls requests from the satellite operator's MCC to the ground station owner's GSS. For Colony II to succeed, the data from the Colony II satellites needs to reach the satellite operator. With the open network nature of the GENSO network there is no guarantee that Colony II data will be gathered when requested. All requests for access are verified at the AUS, and if the AUS determines that Colony II is a lower priority than other missions, the Colony II data may not be collected and therefore lost. Colony II is not the primary mission of GENSO and as such Colony II is subject to the discretion of the AUS controllers. Local versus global control of assets is an issue for any networked system. How GENSO deals with these issues is important to its future.

GENSO's operational architecture allows MCC software to be given to any interested party who wants to fly a satellite without having to provide a ground station. This is an educational boon to programs that cannot afford both the satellite and the ground station. However, should small satellites become widely successful and swamp the existing ground stations, it could lead to a highly stressed system with satellite access requests overwhelming the time available at the limited number of ground stations. Since there is no cost to the MCC user for access to the GENSO network, the system depends on the software optimization to not overwhelm the system. The AUS team culling unnecessary access requests is the only programmatic solution to prevent what would appear as a DoS attack across the network. Since the success of the Colony II program rests heavily on retrieving data from the satellites, this potential risk needs to be clearly addressed before Colony II satellites could rely on the GENSO network.

GENSO ground station hardware differences present yet another limitation with the network. While GENSO supports several different types of ground station setups, there is no standardized requirement for any ground station. The current generation of CubeSats primarily communicates on amateur frequencies from 420 to 450 MHz. Colony II satellites uplink at 450 MHz but downlink at 915 MHz, and will include S-band in the future. GENSO does not currently have hardware support for 915 MHz and S-band equipment. While the proposed GENSO coverage map in Figure 9 looks impressive, it only shows where potential ground stations would provide coverage at some frequency, not necessarily at the frequencies that Colony II satellites use. Additionally, as of September 2011, there is no GENSO coverage in Africa, South America, Asia, or Australia.

While the issues above have not been reported at recent CubeSat Workshops, mitigation of these issues may be of interest in the future. While those currently associated with GENSO support camaraderie and teamwork, relying on software optimization to maintain network availability for Colony II satellites and expecting ground station builders to pay for capabilities above and beyond what they need is unlikely. With these shortcomings and unresolved issues, relying on the GENSO network for Colony II operations is not reasonable at this time.

### 3. NPS Ground Station Opportunities

The MC3 project provides equipment, software, and support that ensures the future success of the Colony II program. Bringing MC3 to NPS provides an educational opportunity for understanding and developing ground station operations for the students and faculty associated with the program. After the MC3 is installed and working properly, the integration of other ground station equipment at NPS could be converted to run with either CGA or GENSO. Building off of the training provided to NPS in the final construction and setup of the MC3, expanded operations with existing equipment will provide additional opportunities for students with a great chance of success since it builds off of existing and functional technology.

Operational experience with the current ground station and with building MC3, NPS faculty and students have developed a solid baseline with which to evaluate other ground station programs. Periodically NPS should revisit the GENSO project to evaluate its evolution and current capabilities. With its potential world-wide participation, GENSO may grow to be the premiere CubeSat ground station network with a refined operational model that maximizes MCC mission team access and respects the GSS ground station operators' equipment. If GENSO matures in such a way that it can provide ground station coverage to Colony II satellites, it can be considered for use in the future. Whether ground stations, satellites, or any other program, NPS needs to constantly evaluate all educational opportunities to continue provide a world-class space education.

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# APPENDIX A. RESTORING CGA INSTRUCTIONS

-------- Original Message --------
**Subject:** Re: MC3 help
**Date:** Thu, 10 Feb 2011 15:27:47 -0500
**From:** [redacted]
**To:** <jhorning@nps.edu>
**CC:** Jim Horning <jahornin@nps.edu>

```
Jim,

To startup CGA, all you should need to do is from a linux prompt type
csm (or cgasm) and it should bring up the system for you.  By doing this
you are starting up the CGA Session Manager.  I think we setup a project
for you that would start up the C1C application (on the Session Manager
under Options->projects).  You can also startup a cmdr by bringing up
the applications window (on the Session Manager under Options-
>applications)

The executable is $CGA_BIN/cometsm.  You can create a short-cut on your
desktop for this if you like.

Your system can also be configured to automatically startup the core CGA
SWBus components upon boot (we currently do this for the operational
MC3's).  I don't remember if we configured your system to do this or
not.  Generally we only do this for the operational systems, not systems
we are doing development on.

If you have any problems or questions, give me a call.  I'm going to be
out of the office tomorrow, but you can reach me on my cell @
[redacted].  Leave me a message if you don't get me & I'll give you a
call as soon as I can.

Thanks
Dean

On 2/10/2011 2:15 PM, Jim Horning wrote:
> Dean,
>
> Apparently the MC3 laptop ([redacted]) does not show the CGA
> software on the desktop.  Do yo know where the main executable is that
> one would invoke to bring up the main CGA software?
>
> Thanks
>
> Jah
>
```

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# APPENDIX B. LIST OF REQUIRED TOOLS

Felt Tip, Permanent Marker

#2 Phillips head screw driver

3/4 inch wrench

Small Flathead screw driver

5/16 inch wrench

Pliers

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# APPENDIX C. HARDIGG RACK PREPARATION

While the case appears completely assembled and ready to use, there is one upgrade that really helps with the assembly of later components: numbering the vertical rack mounts.

1. Count every three screw holes and draw a horizontal line between each set of three screw holes. Each set of three holes in 1 U.

2. Count and label every U of rack space. Start at the top with 1 and continue to the bottom. Markings are shown in Figure 35.


Figure 35. Horizontal Markings with Easy to Reference Numbers Every 1 U

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# APPENDIX D. UPS RACK INSTALLATION

1. Remove the battery from the storage compartment. NOTE: The battery is not yet electrically connected. Removing the battery here will keep the battery safe and lower the weight of the UPS during the installation. Figures 36 through 40 show the installation of the UPS in the rack.

2. Install the L-shaped front rack mounts on the UPS main body.

Figure 36. UPS Front Rack Mounts

3. Install the guides on the UPS main body. Ensure the large flat section of the guides touches the body of the UPS and the raised edge is away from the UPS body.

Figure 37. UPS Rail Guide

4. Install the rail kits in the lowest section of the rack. Rack spaces 20-21 for the NPS installation. Only secure the back of the rail kits with two screws. The front rail faces will be secured after the UPS is installed.

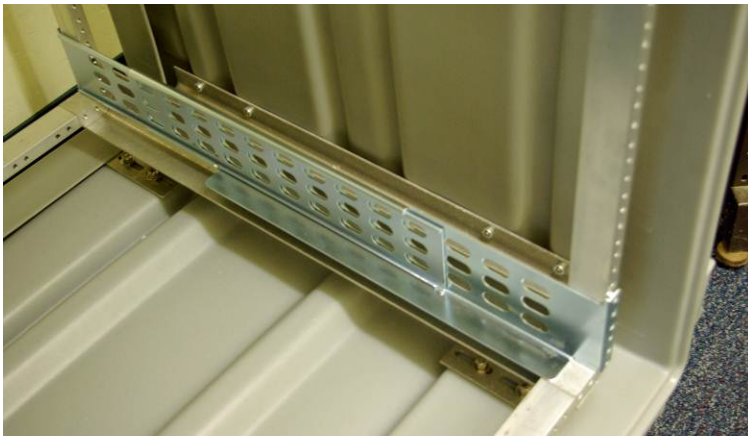

Figure 38. UPS Rail Kit

5. Loop the UPS power cable over the top of the UPS body so it will not catch or bind when installing the UPS in the rack.

6. Slide the UPS into the rail guide ensuring that the guides on the UPS body enter the rails already in the rack.

Figure 39. UPS Rail Guide in the Rail Kit

7. Push the UPS body in until it mates with the front rails and case.

8. Align the UPS, the front rail, and the case and secure the front faces with two screws in both the right and left sides.

9. Move the UPS power cable to a safe position. Curled up and stowed in the space between the bottom of the rack and the UPS will keep it out of the way when moving the case and installing equipment above the UPS.

10. Install the battery and connect it according to the instructions.

11. Install the UPS faceplate, if desired.


Figure 40. UPS Installed

Installing the UPS rail kit as illustrated in step 4 allows the rail kit, and the weight of the UPS, to rest on the rack cross-members. An alternate way to install the rail kit is to screw in the front face of the rail kit to the back of the front rails. This installation method requires using different screw holes for the rail kit and the UPS so the screws do not interfere in the same hole. Also, the weight is transferred from the UPS to the case by the two screws vice the rail kit. One reason to install the front face of the rail kit to the back of the front rails is to obtain a flush fit with the UPS front-mount brackets against the case. This improves ascetics but is more complicated for one person installing the UPS.

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# APPENDIX E. SLIDING RACK SHELF INSTALLATION

Shelves are installed at locations 11, 13, 16, and 19. All shelves are installed in the front plane of the MC3. To install individual racks: Figures 41 through 46 show the installation of the sliding shelves in the rack.

1. Align the front shelving unit to the appropriate rack position.

2. Secure the front with four screws using the top and bottom screw holes. Leave the center screw hole open; it is used to secure the cover plate when the shelf is closed. Figure 41 shows were to install the screws so the front panel will close and secure.

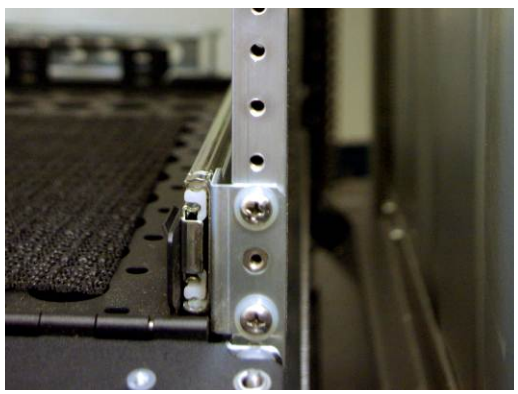

Figure 41. Sliding Rack Shelf–Front Installation

3. Attach the U-shaped clip to the end of the rear rails. For the radio and laptop shelves at positions 19, 16 and 11 install the clip on the right hand side of the case when viewing the rack from the back. This is the same side of the case as the UPS power cord. Install the U-clip for the rotor controller shelf at position 12 on the left hand side.

4. Slide the back rails over the front rails. Secure the back rails to the rear of the rack with four screws using the top and bottom screw holes. Figure 42 shows the installation at the rear of the sliding rack shelf.

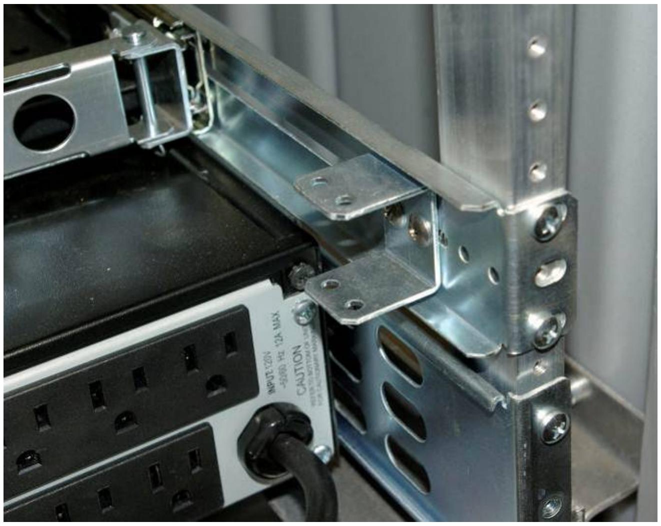

Figure 42. Sliding Rack Shelf–Rear Installation and U-Clip. This shelf is at position 19 and the U-Clip is on the same side as the UPS power cord.

5. Extend the sliding rack shelf until the center of the rack rails are exposed and accessible.

6. Insert two screws in available holes in the rack rails that bind the front rail to the rear rail. The round head screws must be on the inside of the rack. Figure 43 shows the inside of the rack rail.

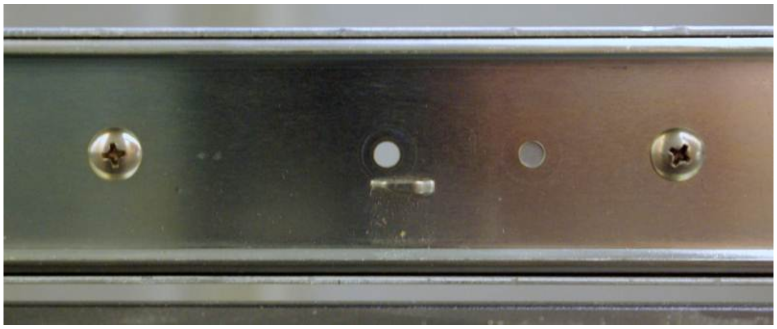

Figure 43. Sliding Rack Shelf – Securing the Front and Rear Rack Rails

7. With the sliding rack shelf still extended install the front U-clip at the back of the shelf. Ensure the front U-clip is on the same side as the back U-clip. The round head screws must be on the outside of the rail to not interfere with shelf operations. Figure 44 shows the front U-clip and the screw installation.

Figure 44. Sliding Rack Shelf – Front U-Clip

8. Install the wire guide arms, hinge pins, and cotter pins. The wire guide arms should rest on top of the front and rear U-clips.

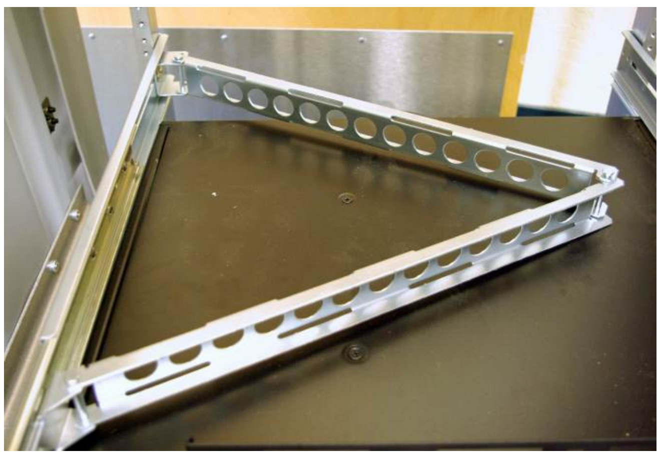

Figure 45. Sliding Rack Shelf – Wire Guide

9. Repeat the installation steps on the remaining shelves.

10. For the radio racks in position 19 and 16 a special modification is required. Due to the size of the ICOM 9100 radio and PS-126 power supply the radio shelves need some slight modification to the tie down tabs. Using pliers bend the four tie down connectors so they are vertical with the edge of the shelf.

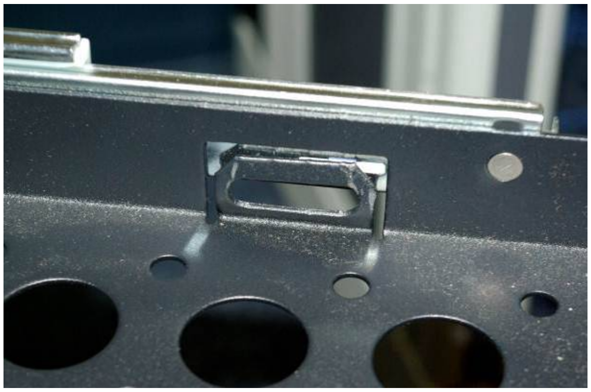

Figure 46. Sliding Rack Shelf – Bent Tie Down on Radio Shelves

# APPENDIX F. GPS TIME SERVER RACK INSTALLATION

1. Install the two rack adapters on the GPS time server.

Figure 47. GPS Time Server – Rack Adapter

2. Install the GPS time server in front position 1. Secure with four screws.


Figure 48. GPS Time Server – Installed

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## APPENDIX G. NETWORK SWITCH RACK INSTALLATION

1. Install the two rack adapters on the network switch.

Figure 49. Network Switch – Rack Adapter

2. Install the network switch in rear position 8. Secure with four screws.


Figure 50. Network Switch – Installed

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# APPENDIX H. POWER DISTRIBUTION UNIT RACK INSTALLATION

To install the Power Tap:

1. Place the Power Tap in the 9 U position on the back plane of the rack.

2. Secure the Power Tap to the rack using four screws, two on both the right and left side. Figure 51 shows the installed power distribution unit.


Figure 51. Power Distribution Unit – Installed

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# APPENDIX I. VPN RACK INSTALLATION

1. Install the two rack adapters on the network switch.

Figure 52. VPN – Rack Adapter

2. Install the network switch in position 2. Secure with four screws.


Figure 53. VPN – Installed

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# APPENDIX J. IC-9100 UHF RADIO RACK INSTALLATION

The IC-9100 and PS-126 are not rack mountable. They are installed on the shelves in position 19 and 16.

1. Remove the handle from the side of the IC-9100. The radio and power supply will not fit on the shelf if the handle is installed.

2. Extend the sliding rack shelf for radio installation.

3. Verify that the tie down connectors are bent out of the way, as shown in Figure 54.

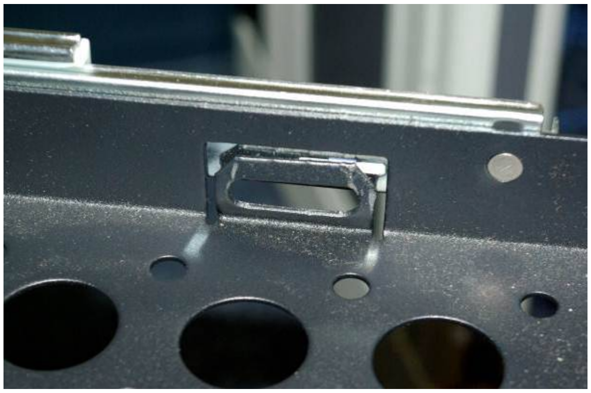

Figure 54. Sliding Rack Shelf – Bent Tie Down on Radio Shelves

4. Place the PS-126 on the left side of the shelf and the IC-9100 on the right side of the shelf. Figure 55 shows the IC-9100 and the PS-126 on the shelf.

Figure 55. IC-9100 and PS-126 – Installed

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# APPENDIX K. G-5500 ROTOR CONTROLLER RACK INSTALLATION

The G-5500 is not rack mountable. The controller boxes are installed on the shelf at position 13.

1. Extend the sliding rack shelf for G-5500 installation.

2. Place the G-5500 on the shelf.

3. Secure the G-5500 in place with zip ties, if desired. It is best do to this step after installing the controller cable to the back of the rear faceplate.

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# APPENDIX L. GS-232B RACK INSTALLATION

The GS-232B is not rack mountable. The controllers rest on top of the G-5500 controllers on the shelf at position 13. Figure 56 shows the GS-232B nested on the G-5500.


Figure 56. GS-232B – Installed Atop G-5500

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# APPENDIX M. UPS POWER CONNECTION

Plug in the UPS to a power source using the permanently attached power cable. This step can be done after all other equipment is installed in the rack.

**NOTE**: The Emergency Power Off (EPO) is not used in the NPS installation.

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# APPENDIX N. GPS TIME SERVER POWER AND DATA CONNECTIONS

## A. POWER INSTALLATION

1. Label the plug end of the power cord with a GPS tag. The handmade GPS tag is shown in Figure 57.


Figure 57. GPS Time Server – Power Cord

2. Plug the power cord into the GPS unit.

3. Route the power cable to the left of the rack, over the top bar and down to the Power Distribution Unit.

4. Plug the power cord into the Power Distribution Unit.

5. Coil and zip tie the center of the power cord so it does not interfere with other equipment. The GPS power cord routing is shown in Figure 58.

Figure 58. GPS Time Server – Power Cable Coil and Routing

## B. DATA CONNECTIONS

### 1. Ethernet Connectivity

1. Label the Ethernet cable with a GPS tag.
2. Plug one end of the Ethernet cable into the LAN 1 port on the GPS time server.

### 2. GPS Connectivity

1. Plug the other end of the Ethernet cable into the network switch.
2. Connect one end of a BNC-BNC cable to the GPS Ant connection on the GPS time server.
3. Connect the other end of the BNC-BNC cable to the inside GPS connection on the rear face plate.
4. Connect the GPS antenna to the GPS connection on the rear faceplate. Figure 59 shows the GPS antenna connected to the rear faceplate. The rear faceplate is installed in Chapter V.


Figure 59. GPS Time Server – External GPS connection

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# APPENDIX O. NETWORK SWITCH POWER AND DATA CONNECTIONS

## A. POWER INSTALLATION

1. Label the plug end of the power cord with a switch tag. The handmade GPS tag is shown in Figure 60.


Figure 60. Network Switch – Power Cord

2. Plug the power cord into the switch unit.

3. Plug the power cord into the Power Distribution Unit.

4. Coil and zip tie the center of the power cord so it does not interfere with other equipment.

## B. DATA CONNECTIONS

The switch does not connect to any outside sources. All data connections to the switch are referenced with the other components.

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# APPENDIX P. POWER DISTRIBUTION UNIT POWER CONNECTION

1. Label the plug end of the power cord with a switch tag.

2. Route the power cable down the left side of the case (when looking at the case from the rear). The cable should run in the void between the plastic shell and the outside of the metal frame to avoid interfering with sliding shelves.

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# APPENDIX Q. VPN POWER AND DATA CONNECTIONS

## A. POWER INSTALLATION

1. Label the plug end of the power cord with a VPN tag.

2. Plug the power cord into the VPN.

3. Route the power cable to the left of the rack, over the top bar and down to the Power Distribution Unit next to the GPS time server power cord.

4. Plug the power cord into the Power Distribution Unit.

5. Coil and zip tie the center of the power cord so it does not interfere with other equipment.

## B. DATA CONNECTIONS

Since the VPN was setup in the current NPS MC3 no data connections were made to the VPN.

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# APPENDIX R. IC-9100 UHF RADIO POWER AND DATA CONNECTIONS

## A. POWER DISTRIBUTION

The ICOM 9100 requires a 13.8 VDC (Voltage Direct Current) connection. The radio comes with a connector and wiring to allow connection into a mobile auto or marine 12 VDC system. For the MC3 installation, a PS-126 13.8 VDC power supply is used. To power the ICOM 9100:

1. Connect the 4-pin power cable from the PS-126 to the ICOM 9100. The 4-pin connector is molded so that it only fits one way, with the latch at the top. Press the connector in to the 9100 until the latch makes a faint popping noise. Figure 61 shows the IC-9100 plugged in to the PS-126.

Figure 61. IC-9100 and PS-126 – Power Supply Connected

2. Label the 120VAC power cord with a radio tag. Indicate which radio it is, i.e., “Top Radio” or “Bottom Radio.”

3. Connect the 3-prong power connection to the PS-126.

4. Route the cable out the back of the shelf, along the cable tray, and down to the UPS.

5. Plug the power cable into the UPS.

## B. DATA CONNECTIONS

Data connections from the USB port to the computer are not made at this time. The drivers for the IC-9100 and CGA are still in development so the computer is unable to control the radio.

RF connections between the radio and the rear faceplate are also not connected. The radios do not directly interface with the antenna equipment. Once the design is finalized and all parts are on hand, the final wiring between the internal components and the rear faceplate can be installed.

# APPENDIX S. G-5500 ROTOR CONTROLLER POWER AND DATA CONNECTIONS

## A. POWER INSTALLATION

The shelf at position 13 will support the Yaesu GS-232B computer interface which is powered by a large transformer. The large transformer will not fit in the power distribution unit due to interference with the network switch. To power all equipment on this shelf:

1. Label the plug end of the power cord with a G-5500 tag.

2. Place the power strip at the back of the shelf with the power cord on the same side as the sliding rack shelf wire guide.

3. Secure the power strip to the sliding rack shelf with zip ties. Be sure not to obstruct any plug receptacles or power switch operation.

4. Route the power strip power cord along the wire guide and plug into the power distribution unit. Figure 62 shows the power strip zip tied to the sliding rack shelf.

Figure 62. G-5500 Power Strip – Installed and Secured

5. Label the plug end of the G-5500 power cord with a G-5500 tag. The handmade G-5500 tag is shown in Figure 63.

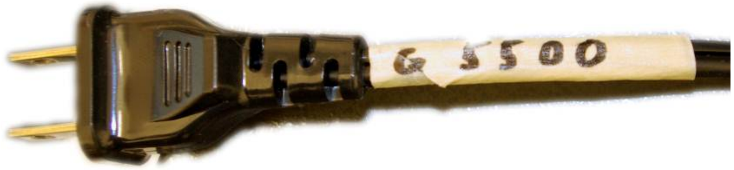


Figure 63. G-5500 – Power Cord

6. Plug in the G-5500 to the power strip. Use the center plugs for the G-5500 to allow for the GS-232 transformers on the ends.

7. Repeat for other G-5500.

## B. DATA CONNECTIONS

These instructions assume that the rear faceplate assembly is already installed. The azimuth and elevation connection on the G-5500 is a 6-screw connection plate. Figures 64 through 72 show the installation of the cables to the G-5500. To install the azimuth and elevation connections:

1. Find azimuth and elevation cables from the back of the faceplate.

2. Strip 3 to 4 inches of the black plastic sheath from the R62 6X18GA wire. The sheath removed allows for the easy routing of the wires in the G-5500 connection plate.


Figure 64. G-5500 AZ/EL Cable – Initial Strip

3. Splay the six wires out so they are easy to work with. Trim any nylon or fiber core back to the level of the black sheath.

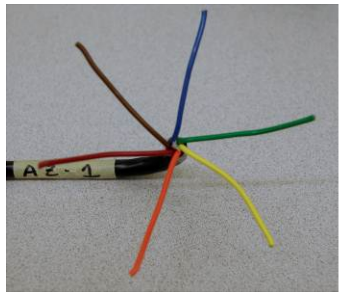


Figure 65. G-5500 AZ/EL Cable – Separated

4. Strip approximately 3/8 inch of each of the six colored wires. Give each wire a slight twist to prevent the individual wires from fraying.

5. Curve the striped wire in a semi-circle. Solder the ends to prevent fraying. Solder-less connectors can also be used here as discussed in the lessons learned.

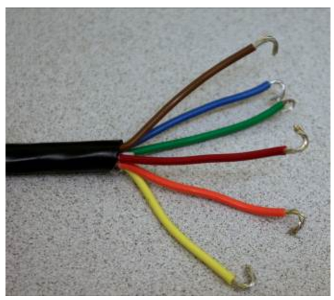

Figure 66. G-5500 AZ/EL Cable – Curved and Soldered

6. Remove the plastic covers from both the azimuth and elevation connection plates.


Figure 67. G-5500 – Cover Plates Removed

7. Loosen the six screws from the azimuth connection plate. The screws should be loose enough to let the easily slide the wire between the connection plate and the wire, but the screw should stay installed in the G-5500.


Figure 68. G-5500 – Screws Loosened but not Removed

8. Insert the orange wire around the number 1 screw. Wrap around from the upper left, clockwise around the screw. Tighten the screw.


Figure 69. G-5500 – Wire 1 Installed

9. Insert the brown wire around the number 2 screw. Wrap around from the upper left, clockwise around the screw. Tighten the screw.

10. Insert the red wire around the number 3 screw. Wrap around from the upper left, clockwise around the screw. Tighten the screw.

11. Insert the green wire around the number 4 screw. Wrap around from the upper left, clockwise around the screw. Tighten the screw.

12. Insert the blue wire around the number 5 screw. Wrap around from the upper left, clockwise around the screw. Tighten the screw.

13. Insert the yellow wire around the number 6 screw. Wrap around from the upper left, clockwise around the screw. Tighten the screw.

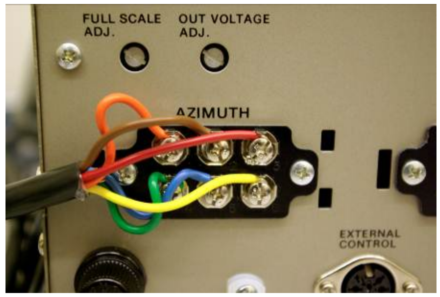


Figure 70. G-5500 – All Six AZ Wires Installed

14. Unscrew the plastic cable holder from the lower portion of the G-5500.

15. Route the cable through the white plastic cable holder. Ensure the flat side of the cable holder is flush against the G-5500.

16. Screw in the cable holder. Orient the cable holder to accommodate the cable. Specific orientation is not required.

17. Repeat the installation steps for the elevation cable. Make sure that the AZ/EL cable pairs go to the same G-5500.


Figure 71. G-5500 – All AZ/EL Connections Installed

18. Label the G-5500 depending on which AZ/EL connections it is mated to, “Top” or “Bottom.”


Figure 72. G-5500 – Labeled “Bottom”

19. Repeat the installation for the second set of AZ/EL cables on the second G-5500.

# APPENDIX T. YAESU-232B POWER AND DATA CONNECTIONS

## A. POWER INSTALLATION

The GS-232B is powered by the NC-72B power adapter. This provides 12 VDC at 500 mA to the unit. To install power:

1. Label the transformer with a GS-232 tag.

2. Plug the yellow tipped adapter into the GS-232B.

3. Plug the adapter into the power strip on the shelf. Figure 73 shows the power strip fully populated on the sliding rack shelf.


Figure 73. GS-232B and G-5500 – Power Connections

## B. DATA CONNECTIONS

The data connections for the GS-232B computer controller consist of a RS-232C connection for the computer and a custom molded AZ/EL connection to the G-5500.

### 1. AL/EL

The GS-232B comes with two different connectors for the AZ/EL ports. The cable with only AZ written on the one white plastic connector is not used. To connect the GS-232B to the G-5500:

1. Connect the two-headed cable to the GS-232B. Ensure the EL-EL and AZ-AZ connections are made properly as the connections are not fit specific. Figure 74 shows the matching AL/EL connections and cables.


Figure 74. GS-232B – AZ/EL Connections

2. Connect the 8-pin adapter to the back of the G-5500 in the External Control port. The indentation at the top of the 8-pin adapter will face upward to match the alignment slot in the G-5500. Figure 75 shows the GS-232B connected to the G-5500.


Figure 75. GS-232B – Connected to G-5500

## 2. RS-232C

The GS-232B comes with an RS-232 port for the connection to the computer. To connect the GS-232 B to the computer:

1. Connect a gender changer to the RS-232 port.
2. Connect a serial cable to GS-232.
3. Connect the serial cable to a Serial to UBS adapter.
4. Connect the USB adapter to the USB hub.

# APPENDIX U. REAR FACEPLATE CONNECTIONS

## A. AZIMUTH AND ELEVATION

The two sets of AZ/EL connections in the faceplate allow the six pin PX0767/S connector to join the azimuth and elevation output of the G-5500 AL/EL controller to each of the antenna masts. Figures 76 through 81 show how to wire the faceplate connectors.

To wire the connectors:

1. Cut approximately 6 to 7 feet of R62 6x18GA cable.

2. Strip approximately 1 1/2 to 2 inches of the outer black sheath to expose the six wires. The actual length is not very important, there needs to be enough wire exposed to easily strip and install the individual wires in the connector.

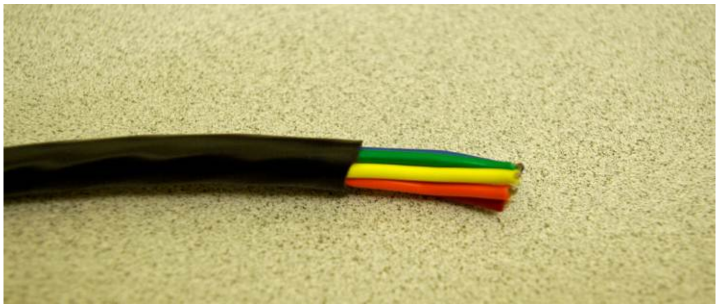

Figure 76. AZ/EL 6-Wire Cable

3. Splay the six wires out so they are easy to work with. Trim any nylon or fiber core back to the level of the black sheath.

4. Strip approximately 1/4 inch of each of the six colored wires. Give each wire a slight twist to prevent the individual wires from fraying.

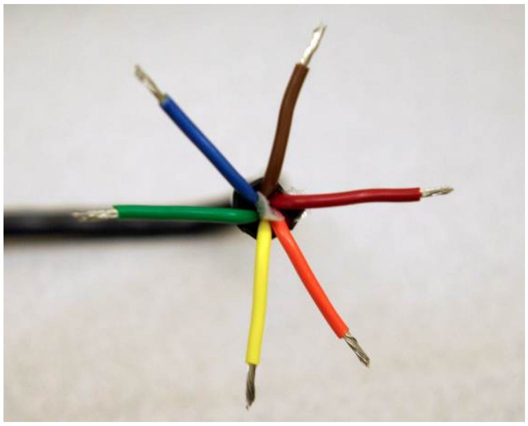

Figure 77. AZ/EL 6-Wire Cable with Trimmed Ends

5. Remove the rubber gasket from the rear of the connector. The rubber gasket is not used for this installation.

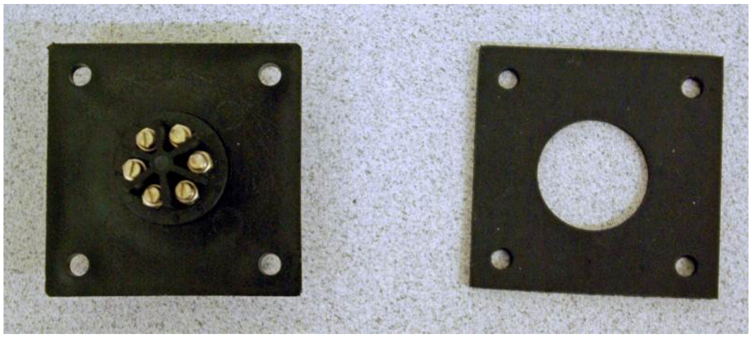

Figure 78. PX0767/S with Rubber Gasket

6. Partially unscrew each setscrew from the back of the connector. The screw should be unscrewed enough to fully open the connection hole, but the screw should remain in the connector.

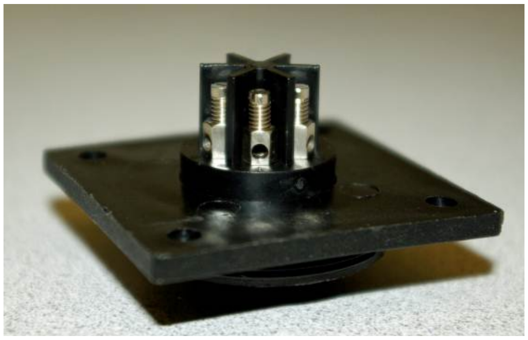

Figure 79. PX0767/S with Open Connection Holes

7. Feed the R62 6x18GA cable through the appropriate hole in the faceplate.

8. Insert the orange wire in the number 1 hole. Tighten the screw.

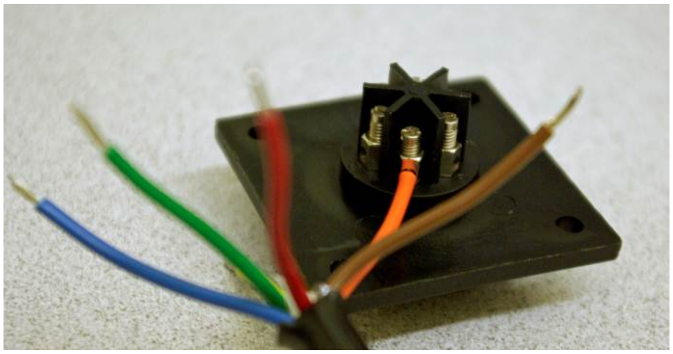

Figure 80. PX0767/S with Number 1 Orange Wire Installed

9. Insert the brown wire in the number 2 hole. Tighten the screw.

10. Insert the red wire in the number 3 hole. Tighten the screw.

11. Insert the green wire in the number 4 hole. Tighten the screw.

12. Insert the blue wire in the number 5 hole. Tighten the screw.

13. Insert the yellow wire in the number 6 hole. Tighten the screw.

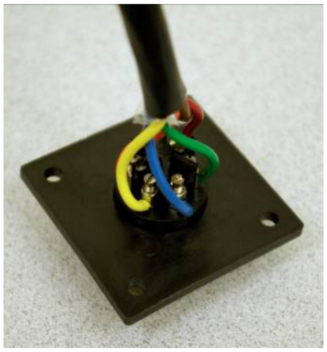

Figure 81. PX0767/S with all Wires Installed

To install the connectors:

1. Slide the connector into the faceplate. Line up the four holes in the connector with the holes in the faceplate. Also, align the connector so that mating slot is

pointing down. Be gentle with feeding the wire through the faceplate; excess force could unseat the wires from the connector. Figure 82 shows the initial alignment of the PX0767/S connector in the faceplate.


Figure 82. PX0767/S Placed in the Faceplate

2. Insert four screws into the four holes.

3. Install one lock washer on each of the four screws.

4. Install one hex nut on each screw. Hand tighten, then tighten the nut with a 5/16-inch wrench approximately 1/4 turn. Do not over tighten. Figure 83 shows the rear of the faceplate with the connector installed.

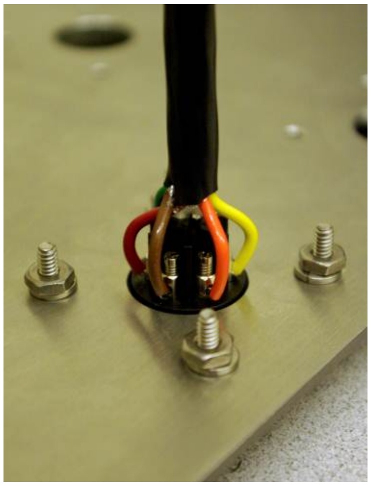

Figure 83. PX0767/S and 6-Wire Cable Installed

5. Install wire identifier on the cable. Figure 84 shows the handmade cable identifiers on all four AZ/EL cables.

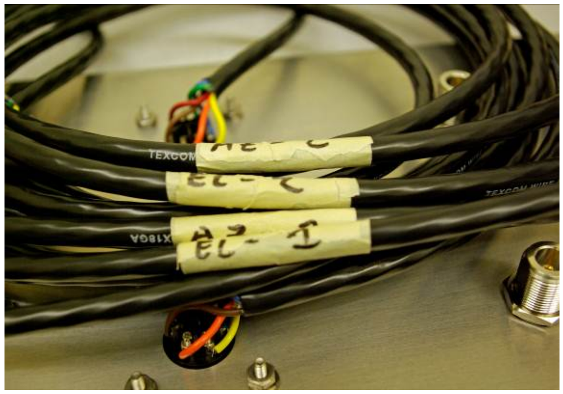

Figure 84. AZ/EL Cables – Wire Identifiers

Repeat the installation and wiring steps for the remaining connectors. Once all four connectors are installed in the faceplate, bind the four AZ/EL cables into one using zip ties. Figure 85 shows all four AZ/EL connectors installed on the faceplate.


Figure 85. AZ/EL – Installed

1. Bind the top AZ/EL cables together and the bottom AZ/EL cables together with zip ties approximately 3 inches from the faceplate.

2. Bind the two, two-cable bundles into one four-cable bundle approximately 1 inch from the previous zip ties. Figure 86 shows the zip tie locations to start the cable bundle.

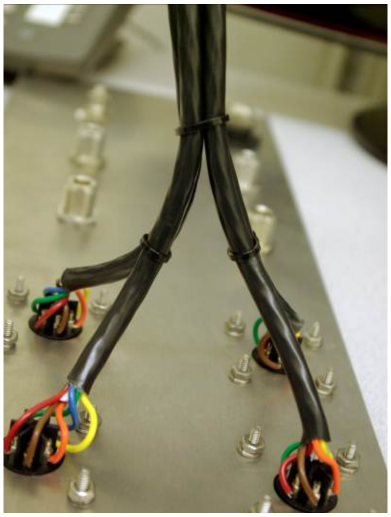

Figure 86. AZ/EL Cable – Initial Binding

3. Continue to bundle the four cables together with zip ties every 8 to 12 inches as needed. The space in between the zip ties is determined by how the cables spread, their tendencies to stick together or spread apart, and the aesthetic appeal of a cohesive cable bundle. Figure 87 shows the zip tie spacing distance used for the NPS installation.

Figure 87. AZ/EL Cable – Zip Tie Spacing and No Twists

4. Stop the zip ties approximately 18 to 24 inches from the end of the cable to allow sufficient flexibility to install the cables to their respective G-5500.

## B. RF CONNECTORS–UHF RECEIVE, UHF TRANSMIT, S-BAND RECEIVE, S-BAND TRANSMIT

The four RF connections in the faceplate are N Jack to Jack bulkhead connectors. The connector is either a Digi-Key ARF1713-ND or a Mouser 523-172124. Figures 88 through 92 show the RF connector installation steps. To install the connectors:

1. If required, dissemble the connector, hex nut, lock washer and rubber gasket.

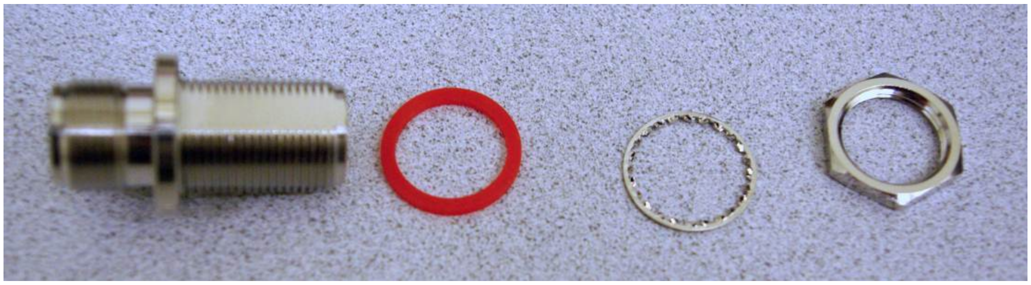

Figure 88. RF Connector - Dissembled

2. Place the rubber gasket on the connector from the side with the threads. The gasket should loosely seat itself in the cup of the connector plate.

Figure 89. RF Connector –Gasket Installed

3. Slide the connector into the faceplate so that the flat faces in the connector align with the flat faces in the faceplate. Insure the connector face is on the outside of the faceplate so that the lock washer and hex nut will go on the inside of the faceplate.

4. Install the star washer on the connector.

Figure 90. RF Connector – Installed in Faceplate with Star Washer

5. Install hex nut on the connector. Hand tighten then tighten the nut with a 3/4-inch wrench approximately 1/4 turn. Do not over tighten.

Figure 91. RF Connector – Installed, Back

6. Repeat the installation steps for the remaining RF connectors.


Figure 92. RF Connectors – Installed

## C. ETHERNET

The Ethernet faceplate connection is a double-ended, female-female, RJ-45 connection that allows an external Ethernet cable to enter the MC3. The connector is a Digi-Key 708-1009-ND screw in connector. Figures 93 through 95 show the Ethernet connector installation steps. To install the connector:

1. Unscrew the plastic hex nut from the connector.

Figure 93. Ethernet – Hex Nut Removed

2. Align the rubber washer so that the notch on the inside of the rubber washer aligns with the key on the connector.

3. Slide the connector into the faceplate so that the key in the connector aligns with the notch in the face plate. Insure the rubber washer is on the outside of the faceplate so that the plastic hex nut will go on the inside of the faceplate.

4. Install the plastic hex nut on the connector. Screw the connection hand tight.

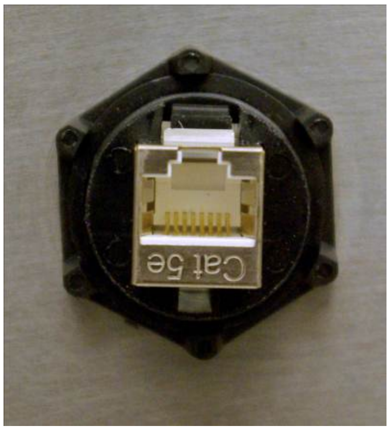

Figure 94. Ethernet – Installed, Back


Figure 95. Ethernet – Installed, Front

## D. GPS

The GPS faceplate connection is a double-ended, female-female, BNC connection that allows the GPS antenna to attach to the MC3 at an easy to reach place while never needing to dig into the back of the GPS time server. The connector is a Digi-Key A24556-ND screw in connector. Figures 96 through 100 show the GPS connector installation steps. To install the connector:

1. If required, dissemble the connector, hex nut, star washer, and rubber gasket.

Figure 96. GPS Connector - Disassembled

2. Place the rubber gasket on the connector from the side with the threads. The gasket should loosely seat itself in the cup of the connector plate.

Figure 97. GPS Connector – Gasket Installed

3. Slide the connector into the faceplate so that the flat in the connector aligns with the flat in the faceplate. Insure the connector face is on the outside of the faceplate so that the star washer and hex nut will go on the inside of the faceplate.

4. Install the star washer on the connector.

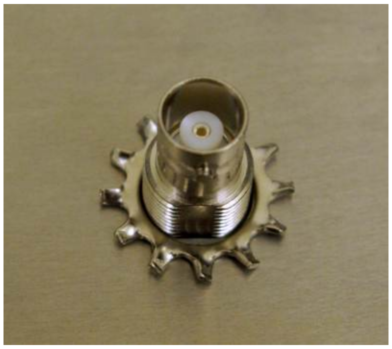

Figure 98. GPS Connector – Installed in Faceplate with Star Washer

5. Install hex nut on the connector. Hand tighten then tighten the nut with a 3/4-inch wrench approximately 1/4 turn. Do not over tighten.

Figure 99. GPS Connector – Installed, Back


Figure 100. GPS Connector – Installed, Front

# APPENDIX V. EXTERNAL AZ/EL ROTOR CABLE CONNECTORS

The AZ/EL rotor cables connect the MC3 faceplate connection to the actual rotor at the top of the antenna mast. Figures 101 through 108 show selected steps to help wire the AZ/EL connector. To wire the 6-pin faceplate connectors:

1. Remove the retaining washer and the screw collar from the 6-pin connector.

Figure 101. AZ/EL Connector – Partial Disassembly

2. Unscrew the hex headed retainer nut from the back of the 6-pin connector. Remove the white plastic star shaped wire holder and the rubber insulator.

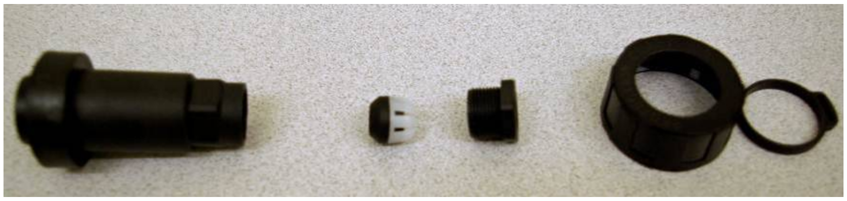

Figure 102. AZ/EL Connector – Rear Disassembly

3. Remove the center connector. Do this by unscrewing the cruciform retaining ring at the plug end of the connector. A small screwdriver, used with caution, can be used to unscrew the retaining ring.

Figure 103. AZ/EL Connector – Unscrewing the Retaining Ring

Figure 104. AZ/EL Connector – Full Disassembly

NOTE: The cable used in these pictures is an 8-wire cable with a different wire color to pin number scheme than the 6-wire cable used to connect the G-5500 to the face plane. If using the R62 6x18GA cable maintain that color scheme. The colors listed here in the instructions are the same as the colors listed in the faceplate AZ/EL instructions.

4. Strip approximately 1 to 1 1/2 inches of the outer sheath to expose the six wires. The actual length is important here as the sheath needs to feed into the wire holder and rubber gasket inside the 6-pin connector.

5. Splay the six wires out so they are easy to work with. Trim any nylon or fiber core back to the level of the black sheath.

6. Strip approximately 1/4 inch of each of the six colored wires. Give each wire a slight twist to prevent the individual wires from fraying.

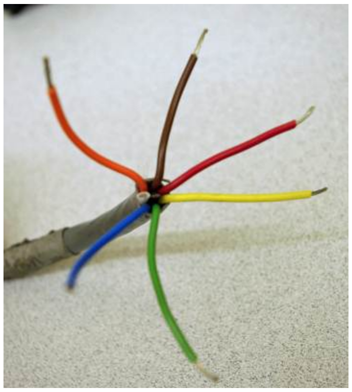

Figure 105. AZ/EL Cable – Stripped, Splayed, and Twisted

7. Place the 6-pin connector components on the wire in the reverse order of assembly. Start with the retaining washer and screw collar removed in step 1. Continue with the small threaded hex nut followed by the white star wire holder, the rubber insulator, and then the main connector body.

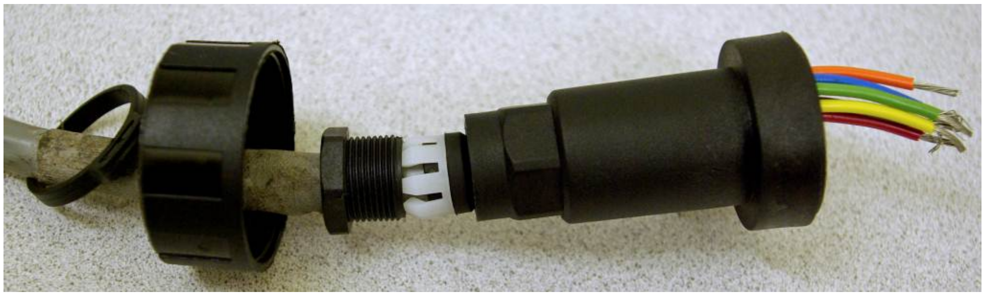

Figure 106. AZ/EL Cable – Fed Through Connector Body

8. Partially unscrew each setscrew from the back of the connector. The screw should be unscrewed enough to fully open the connection hole, but the screw should remain in the connector.

9. Insert the orange wire in the number 1 hole. Tighten the screw.

10. Insert the brown wire in the number 2 hole. Tighten the screw.

11. Insert the red wire in the number 3 hole. Tighten the screw.

12. Insert the green wire in the number 4 hole. Tighten the screw.

13. Insert the blue wire in the number 5 hole. Tighten the screw.

14. Insert the yellow wire in the number 6 hole. Tighten the screw.

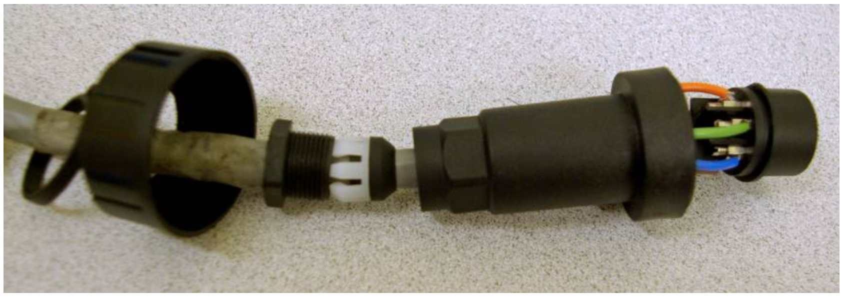

Figure 107. AZ/EL Cable – Wires Attached

15. Slide the main connector body up to meet the wired connector.

16. Install the retaining ring at the plug end of the connector.

17. Push the rubber insulator and the white plastic wire holder firmly into the connector body.

18. Screw in the hex headed retainer nut.

Figure 108. AZ/EL Cable – Connector Secured from Front and Rear

19. Replace the retaining washer and the screw collar on the body of the 6-pin adapter.

Repeat the above steps for all four AZ/EL rotor cables.

# APPENDIX W. 450 MHZ UPLINK MARGIN

| | | | | | |
|---|---|---|---|---|---|
| S/C Altitude | alt | | 770 | km | |
| Frequency | f | | 0.45 | GHz | |
| Data Rate | DataRate | Boeing | 9.6 | kbps | |
| Bit Error Rate | BitError | Boeing | 1.E-05 | | |
| Required Eb/No | Eb_No_Req | Boeing - GMSK modulation | 9.6 | dB | |
| Atmospheric Losses | L_a | Boeing | -0.17 | dB | |
| Ionospheric Losses | L_i | Boeing | -0.2 | dB | |
| | | | | | |
| Transmitter - Ground Station | | | | | |
| Transmitter Power | Power | | 25 | Watts | |
| Transmitter Power | P | | 13.98 | dBW | =10*LOG(Power) |
| Transmission Line Loss | TX_ll | SMAD 550 (Table13-10) | -0.50 | dB | |
| Antenna Gain | GND_Ga | M2 Antenna | 14.15 | dB | |
| Antenna Pointing Error | e_gnd | | 1 | deg | |
| Antenna Half Power Beamwidth | θ | M2 Antenna | 30 | deg | |
| Antenna Pointing Error | Lθ | SMAD pg 556 (EQ 13-21) | -0.01 | dB | =-12*(e_gnd/θ)^2 |
| GND Line Loss | GND_Ll | | -0.50 | dB | |
| Transmitter EIRP | TX_EIRP | | 27.12 | dbW | =SUM(P,TX_ll,GND_Ga,Lθ,GND_Ll) |
| | | | | | |
| Receiver - Space Craft | | | | | |
| Receiver Noise Temp | R_NT | Boeing | 597 | k | |
| Receiver Bandwidth | R_Bw | | 0.2 | MHz | |
| S/C Antenna Point Loss | SC_Lp | Boeing | -1 | dB | |
| S/C Antenna Gain | SC_Ga | Boeing | 2 | dB | |
| S/C Transmission Line Loss | SC_Ll | Boeing | -0.5 | dB | |
| S/C Polarization Loss | SC_Lpolar | Boeing | -3 | dB | |
| | | | | | |
| Total Received Noise Power | N | | -147.83 | dB | =10*LOG(1.38E-23*R_NT*(R_Bw*1000000)) |
| Received Noise Spectral Density | No | | -200.84 | dB | =10*LOG(1.38E-23*R_NT) |

| Elevation Angle (deg) | Space Craft Distance (km) | Space Loss (dB) (SMAD 13-23b) | Received Carrier Power (dBW) | Received Carrier to Noise Ratio (dB) | Received Energy Per Bit (dB) | Calculated Eb/No (dB) | Margin (dB) |
|---|---|---|---|---|---|---|---|
| 0 | 3227 | -155.69 | -131.44 | 16.39 | -171.27 | 29.57 | 19.97 |
| 5 | 2719 | -154.20 | -129.96 | 17.88 | -169.78 | 31.06 | 21.46 |
| 10 | 2304 | -152.77 | -128.52 | 19.31 | -168.34 | 32.50 | 22.90 |
| 15 | 1974 | -151.42 | -127.18 | 20.66 | -167.00 | 33.84 | 24.24 |
| 20 | 1714 | -150.19 | -125.95 | 21.88 | -165.77 | 35.07 | 25.47 |
| 25 | 1509 | -149.09 | -124.84 | 22.99 | -164.67 | 36.17 | 26.57 |
| 30 | 1348 | -148.11 | -123.86 | 23.97 | -163.68 | 37.16 | 27.56 |
| 35 | 1220 | -147.24 | -123.00 | 24.84 | -162.82 | 38.02 | 28.42 |
| 40 | 1118 | -146.48 | -122.24 | 25.60 | -162.06 | 38.78 | 29.18 |
| 45 | 1036 | -145.82 | -121.57 | 26.26 | -161.40 | 39.45 | 29.85 |
| 50 | 970 | -145.25 | -121.00 | 26.83 | -160.82 | 40.02 | 30.42 |
| 55 | 916 | -144.76 | -120.51 | 27.32 | -160.33 | 40.51 | 30.91 |
| 60 | 874 | -144.34 | -120.10 | 27.74 | -159.92 | 40.92 | 31.32 |
| 65 | 840 | -144.00 | -119.75 | 28.08 | -159.58 | 41.27 | 31.67 |
| 70 | 814 | -143.72 | -119.48 | 28.35 | -159.30 | 41.54 | 31.94 |
| 75 | 794 | -143.51 | -119.27 | 28.57 | -159.09 | 41.75 | 32.15 |
| 80 | 781 | -143.36 | -119.12 | 28.71 | -158.94 | 41.90 | 32.30 |
| 85 | 773 | -143.27 | -119.03 | 28.80 | -158.85 | 41.99 | 32.39 |
| 90 | 770 | -143.24 | -119.00 | 28.83 | -158.82 | 42.02 | 32.42 |

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# APPENDIX X. 2.1 GHZ UPLINK MARGIN

| | | | | | |
|---|---|---|---|---|---|
| S/C Altitude | alt | | 770 | km | |
| Frequency | f | | 2.1 | GHz | |
| Data Rate | DataRate | Boeing | 9.6 | kbps | |
| Bit Error Rate | BitError | Boeing | 1.E-05 | | |
| Required Eb/No | Eb_No_Req | Boeing - GMSK modulation | 9.6 | dB | |
| Atmospheric Losses | L_a | Boeing | -0.14 | dB | |
| Ionospheric Losses | L_i | Boeing | -0.2 | dB | |
| | | | | | |
| Transmitter - Ground Station | | | | | |
| Transmitter Power | Power | | 1 | Watts | |
| Transmitter Power | P | | 0.00 | dBW | =10*LOG(Power) |
| Transmitter Line Loss | TX_ll | SMAD 550 (Table13-10)/Boeing | -0.50 | dB | |
| Antenna Gain | GND_Ga | M2 Antenna | 17.25 | dB | |
| Antenna Pointing Error | e_gnd | | 1 | deg | |
| Antenna Half Power Beamwidth | θ | M2 Antenna | 27 | deg | |
| Antenna Pointing Error | Lθ | SMAD pg 556 (EQ 13-21) | -0.02 | dB | =-12*(e_gnd/θ)^2 |
| GND Line Loss | GND_Ll | | -0.50 | dB | |
| GND Amp Noise | GND_Amp_g | ZHL-3W-252+ graph | 50.50 | dB | |
| GND Amp Gain | GND_Amp_n | ZHL-3W-252+ graph | -5.80 | dB | |
| Transmitter EIRP | TX_EIRP | | 60.93 | dbW | =SUM(P,TX_ll,GND_Ga,Lθ,GND_Ll,GND_Amp_g,GND_Amp_n) |
| | | | | | |
| Receiver - Space Craft | | | | | |
| Receiver Noise Temp | R_NT | Boeing | 616 | k | |
| Receiver Bandwidth | R_Bw | | 0.2 | MHz | |
| S/C Antenna Point Loss | SC_Lp | Boeing | -1 | dB | |
| S/C Antenna Gain | SC_Ga | Boeing | 3 | dB | |
| S/C Transmission Line Loss | SC_Ll | Boeing | -1 | dB | |
| S/C Polarization Loss | SC_Lpolar | Boeing | -0.3 | dB | |
| | | | | | |
| Total Received Noise Power | N | | -147.70 | dB | =10*LOG(1.38E-23*R_NT*(R_Bw*1000000)) |
| Received Noise Spectral Density | No | | -200.71 | dB | =10*LOG(1.38E-23*R_NT) |

| Elevation Angle (deg) | Space Craft Distance (km) | Space Loss (dB) (SMAD 13-23b) | Received Carrier Power (dBW) | Received Carrier to Noise Ratio (dB) | Received Energy Per Bit (dB) | Calculated Eb/No (dB) | Margin (dB) |
|---|---|---|---|---|---|---|---|
| 0 | 3227 | -169.07 | -107.78 | 39.92 | -147.60 | 53.11 | 43.51 |
| 5 | 2719 | -167.58 | -106.29 | 41.41 | -146.11 | 54.59 | 44.99 |
| 10 | 2304 | -166.15 | -104.85 | 42.84 | -144.67 | 56.03 | 46.43 |
| 15 | 1974 | -164.80 | -103.51 | 44.19 | -143.33 | 57.37 | 47.77 |
| 20 | 1714 | -163.57 | -102.28 | 45.41 | -142.10 | 58.60 | 49.00 |
| 25 | 1509 | -162.47 | -101.18 | 46.52 | -141.00 | 59.71 | 50.11 |
| 30 | 1348 | -161.49 | -100.19 | 47.50 | -140.02 | 60.69 | 51.09 |
| 35 | 1220 | -160.62 | -99.33 | 48.37 | -139.15 | 61.55 | 51.95 |
| 40 | 1118 | -159.86 | -98.57 | 49.13 | -138.39 | 62.31 | 52.71 |
| 45 | 1036 | -159.20 | -97.91 | 49.79 | -137.73 | 62.98 | 53.38 |
| 50 | 970 | -158.63 | -97.33 | 50.36 | -137.16 | 63.55 | 53.95 |
| 55 | 916 | -158.14 | -96.84 | 50.85 | -136.67 | 64.04 | 54.44 |
| 60 | 874 | -157.72 | -96.43 | 51.27 | -136.25 | 64.45 | 54.85 |
| 65 | 840 | -157.38 | -96.09 | 51.61 | -135.91 | 64.80 | 55.20 |
| 70 | 814 | -157.10 | -95.81 | 51.89 | -135.63 | 65.07 | 55.47 |
| 75 | 794 | -156.89 | -95.60 | 52.10 | -135.42 | 65.28 | 55.68 |
| 80 | 781 | -156.74 | -95.45 | 52.25 | -135.27 | 65.43 | 55.83 |
| 85 | 773 | -156.65 | -95.36 | 52.33 | -135.18 | 65.52 | 55.92 |
| 90 | 770 | -156.62 | -95.33 | 52.36 | -135.15 | 65.55 | 55.95 |

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# APPENDIX Y. 915 MHZ DOWNLINK MARGIN

| | | | | | |
|---|---|---|---|---|---|
| S/C Altitude | alt | | 770 | km | |
| Frequency | f | | 0.915 | GHz | |
| Data Rate | DataRate | Boeing | 50.0 | kbps | |
| Bit Error Rate | BitError | Boeing | 1.E-05 | | |
| Required Eb/No | Eb_No_Req | Boeing - GMSK modulation | 9.6 | dB | |
| Atmospheric Losses | L_a | Boeing | -0.17 | dB | |
| Ionospheric Losses | L_i | Boeing | -0.2 | dB | |
| | | | | | |
| Transmitter - Space Craft | | | | | |
| Transmitter Power | Power | Boeing | 2 | Watts | |
| Transmitter Power | P | | 3.01 | dBW | =10*LOG(Power) |
| S/C Transmission Line Loss | SC_Ll | Boeing | -0.5 | dB | |
| S/C Polarization Loss | SC_Lpolar | Boeing | -3 | dB | |
| S/C Antenna Gain | SC_Ga | Boeing | 2 | dB | |
| S/C Antenna Point Loss | SC_Lp | Boeing | -1 | dB | |
| S/C Filter Loss | SC_Filter | Boeing | -0.5 | db | |
| Transmitter EIRP | TX_EIRP | | 0.01 | dbW | =SUM(P,SC_Ll,SC_Lpolar,SC_Ga,SC_Lp,SC_Filter) |
| | | | | | |
| Receiver - Ground Station | | | | | |
| Receiver Noise Temp | R_NT | Earth Temp | 300 | k | |
| Receiver Bandwidth | R_Bw | | 0.2 | MHz | |
| GND Line Loss | GND_Line_L | | -0.50 | dB | |
| GND Antenna Gain | GND_Ga | M2 Antenna | 18.5 | dB | |
| GND Antenna Pointing Error | e_gnd | | 1 | deg | |
| GND Antenna Half Power Beamwidth | θ | M2 Antenna | 21 | deg | |
| Antenna Pointing Error | Lθ | SMAD pg 556 (EQ 13-21) | -0.03 | dB | =-12*(e_gnd/θ)^2 |
| GND LNA Gain | GND_LNA_g | ZQL-900MLNW Graph | 25.50 | dB | |
| GND LNA Noise | GND_LNA_n | ZQL-900MLNW Graph | -1.35 | dB | |
| | | | | | |
| Total Received Noise Power | N | | -150.82 | dB | =10*LOG(1.38E-23*R_NT*(R_Bw*1000000)) |

| Elevation Angle (deg) | Space Craft Distance (km) | Space Loss (dB) (SMAD 13-23b) | Received Carrier Power (dBW) | Received Carrier to Noise Ratio (dB) | Received Energy Per Bit (dB) | Calculated Eb/No (dB) | Margin (dB) |
|---|---|---|---|---|---|---|---|
| 0 | 3227 | -161.86 | -120.09 | 30.73 | -167.08 | 36.75 | 27.15 |
| 5 | 2719 | -160.37 | -118.60 | 32.22 | -165.59 | 38.24 | 28.64 |
| 10 | 2304 | -158.93 | -117.17 | 33.65 | -164.16 | 39.67 | 30.07 |
| 15 | 1974 | -157.59 | -115.82 | 35.00 | -162.81 | 41.02 | 31.42 |
| 20 | 1714 | -156.36 | -114.60 | 36.22 | -161.58 | 42.25 | 32.65 |
| 25 | 1509 | -155.25 | -113.49 | 37.33 | -160.48 | 43.35 | 33.75 |
| 30 | 1348 | -154.27 | -112.51 | 38.31 | -159.50 | 44.33 | 34.73 |
| 35 | 1220 | -153.41 | -111.64 | 39.18 | -158.63 | 45.20 | 35.60 |
| 40 | 1118 | -152.65 | -110.88 | 39.94 | -157.87 | 45.96 | 36.36 |
| 45 | 1036 | -151.98 | -110.22 | 40.60 | -157.21 | 46.62 | 37.02 |
| 50 | 970 | -151.41 | -109.65 | 41.17 | -156.64 | 47.19 | 37.59 |
| 55 | 916 | -150.92 | -109.16 | 41.66 | -156.15 | 47.68 | 38.08 |
| 60 | 874 | -150.51 | -108.74 | 42.08 | -155.73 | 48.10 | 38.50 |
| 65 | 840 | -150.16 | -108.40 | 42.42 | -155.39 | 48.44 | 38.84 |
| 70 | 814 | -149.89 | -108.12 | 42.70 | -155.11 | 48.72 | 39.12 |
| 75 | 794 | -149.68 | -107.91 | 42.91 | -154.90 | 48.93 | 39.33 |
| 80 | 781 | -149.53 | -107.76 | 43.06 | -154.75 | 49.08 | 39.48 |
| 85 | 773 | -149.44 | -107.67 | 43.15 | -154.66 | 49.17 | 39.57 |
| 90 | 770 | -149.41 | -107.65 | 43.17 | -154.63 | 49.20 | 39.60 |

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# APPENDIX Z. 2.2 GHZ DOWNLINK MARGIN

| | | | | | |
|---|---|---|---|---|---|
| S/C Altitude | alt | | 770 | km | |
| Frequency | f | | 2.2 | GHz | |
| Data Rate | DataRate | Boeing | 512.0 | kbps | |
| Bit Error Rate | BitError | Boeing | 1.E-05 | | |
| Required Eb/No | Eb_No_Req | Boeing - GMSK modulation | 9.6 | dB | |
| Atmospheric Losses | L_a | Boeing | -0.14 | dB | |
| Ionospheric Losses | L_i | Boeing | -0.2 | dB | |
| | | | | | |
| Transmitter - Space Craft | | | | | |
| Transmitter Power | Power | Boeing - minimum required | 2 | Watts | |
| Transmitter Power | P | | 3.01 | dBW | =10*LOG(Power) |
| S/C Transmission Line Loss | SC_Ll | Boeing | -1.5 | dB | |
| S/C Polarization Loss | SC_Lpolar | Boeing | -0.3 | dB | |
| S/C Antenna Gain | SC_Ga | Boeing | 3 | dB | |
| S/C Antenna Point Loss | SC_Lp | Boeing | -1 | dB | |
| Transmitter EIRP | TX_EIRP | | 3.21 | dbW | =SUM(P,SC_Ll,SC_Lpolar,SC_Ga,SC_Lp) |
| | | | | | |
| Receiver - Ground Station | | | | | |
| Receiver Noise Temp | R_NT | Earth Temp | 300 | k | |
| Receiver Bandwidth | R_Bw | | 0.2 | MHz | |
| GND Line Loss | GND_Line_L | | -0.50 | dB | |
| GND Antenna Gain | GND_Ga | M2 Antenna | 21 | dB | |
| GND Antenna Pointing Error | e_gnd | | 1 | deg | |
| GND Antenna Half Power Beamwidth | θ | M2 Antenna | 13 | deg | |
| Antenna Pointing Error | Lθ | SMAD pg 556 (EQ 13-21) | -0.07 | dB | =-12*(e_gnd/θ)^2 |
| GND LNA Gain | GND_LNA_g | ZQL-2700MLNW+ | 30.15 | dB | |
| GND LNA Noise | GND_LNA_n | ZQL-2700MLNW+ | -0.80 | dB | |
| | | | | | |
| Total Received Noise Power | N | | -150.82 | dB | =10*LOG(1.38E-23*R_NT*(R_Bw*1000000)) |
| Received Noise Spectral Density | No | | -203.83 | dB | =10*LOG(1.38E-23*R_NT) |

| Elevation Angle (deg) | Space Craft Distance (km) | Space Loss (dB) (SMAD 13-23b) | Received Carrier Power (dBW) | Received Carrier to Noise Ratio (dB) | Received Energy Per Bit (dB) | Calculated Eb/No (dB) | Margin (dB) |
|---|---|---|---|---|---|---|---|
| 0 | 3227 | -169.48 | -116.83 | 33.99 | -173.92 | 29.91 | 20.31 |
| 5 | 2719 | -167.99 | -115.34 | 35.48 | -172.43 | 31.40 | 21.80 |
| 10 | 2304 | -166.55 | -113.90 | 36.92 | -170.99 | 32.84 | 23.24 |
| 15 | 1974 | -165.21 | -112.56 | 38.26 | -169.65 | 34.18 | 24.58 |
| 20 | 1714 | -163.98 | -111.33 | 39.49 | -168.42 | 35.41 | 25.81 |
| 25 | 1509 | -162.87 | -110.23 | 40.59 | -167.32 | 36.51 | 26.91 |
| 30 | 1348 | -161.89 | -109.24 | 41.58 | -166.34 | 37.49 | 27.89 |
| 35 | 1220 | -161.03 | -108.38 | 42.44 | -165.47 | 38.36 | 28.76 |
| 40 | 1118 | -160.27 | -107.62 | 43.20 | -164.71 | 39.12 | 29.52 |
| 45 | 1036 | -159.60 | -106.95 | 43.87 | -164.05 | 39.78 | 30.18 |
| 50 | 970 | -159.03 | -106.38 | 44.44 | -163.47 | 40.36 | 30.76 |
| 55 | 916 | -158.54 | -105.89 | 44.93 | -162.98 | 40.85 | 31.25 |
| 60 | 874 | -158.13 | -105.48 | 45.34 | -162.57 | 41.26 | 31.66 |
| 65 | 840 | -157.78 | -105.13 | 45.69 | -162.23 | 41.60 | 32.00 |
| 70 | 814 | -157.51 | -104.86 | 45.96 | -161.95 | 41.88 | 32.28 |
| 75 | 794 | -157.30 | -104.65 | 46.17 | -161.74 | 42.09 | 32.49 |
| 80 | 781 | -157.15 | -104.50 | 46.32 | -161.59 | 42.24 | 32.64 |
| 85 | 773 | -157.06 | -104.41 | 46.41 | -161.50 | 42.33 | 32.73 |
| 90 | 770 | -157.03 | -104.38 | 46.44 | -161.47 | 42.36 | 32.76 |

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